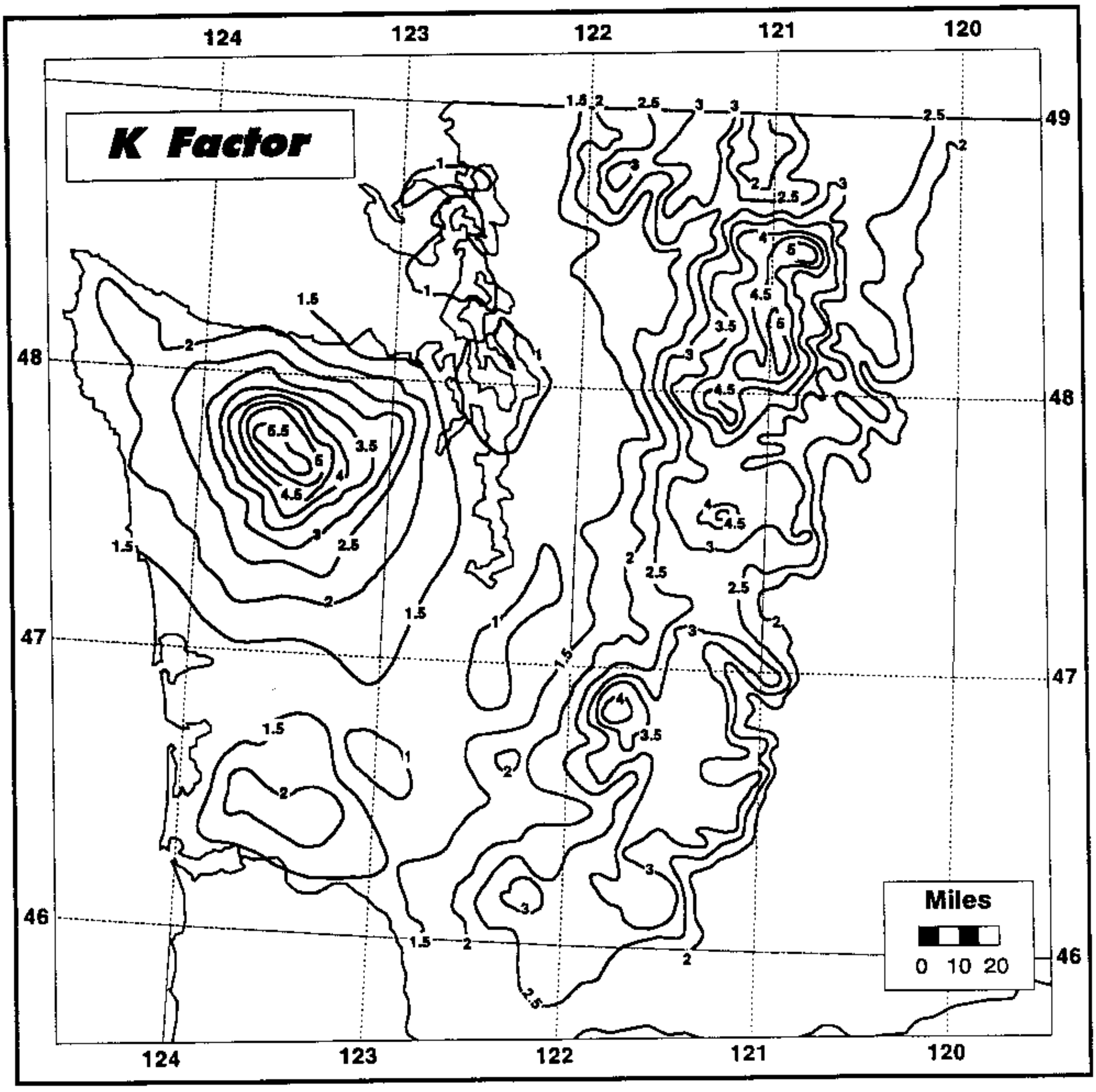

Figure 8.4.--Analysis of orographic factor, K, for western Washington.

9. THE GENERAL STORM PMP INDEX MAP AND SEASONAL VARIATION

Development of the 10-mi^2, 24-hour index map of general storm PMP was accomplished in two phases; the first was the specification of the orographic factor K across the region. Development and discussion of the K-factor chart is found in Section 8.3. Second was multiplication of the K-factor by the depth of non-orographic PMP at 10-mi^2 and 24-hours. The non-orographic PMP (or FAFP) analysis is discussed in Section 7.5. The index value of total PMP is produced by adjustment of FAFP from sea level to the barrier elevation. This procedure is much the same as that used in HMR 55A to produce the 10-mi^2, 24-hour index map in that study; the only significant difference being that in this report, the analysis of FAFP was done at sea level rather than on the undulating surface represented by the barrier elevation.

Computation of the general storm total PMP index map for 10-mi^2, 24 hours at barrier elevation was made at each grid point of the 0.1-inch grid used by Reclamation and a computer analyzed product was developed at 1:1,000,000 scale for the region of study. Typical of many computer analyses, the level of smoothing is not sufficient to eliminate all of the discontinuities. The technique also produced some features believed to be insignificant to the study, such as enclosed isolines for areas less than 10 mi^2. For these and other reasons, a hand-smoothed overlay was drawn to provide the final analysis of total general storm PMP for this study. Subsequently, the hand drawn analysis was digitized using the U.S. Army Corps of Engineers GRASS geographic information system.

Figure 9.1 shows a portion of the final digitized general storm PMP index map (10-mi^2, 24 hours) for the northwest corner of the region. The portion of the region shown in Figure 9.1 is primarily controlled by only two major storms, storm 80 through the Olympic Mountains and the Seymour Falls (British Columbia) storm through the Puget Sound basin and the Cascades. Extreme sheltering by the Olympics is noted as the maximum 10-mi^2, 24-hour PMP of 38 inches drops off to less than 8 inches to the immediate northeast of this barrier. The Cascades support PMP estimates as high as 29 inches, with a leeward drop-off to 8 to 9 inches.

The complete 10-mi^2, 24-hour total general storm PMP index maps at 1:1,000,000 scale are available as four regional maps (Maps 1-4, representing the NW, NE, SE and SW quadrants, respectively) in the package accompanying this report. These oversized maps are used with the computational procedure outlined in Chapter 15. Maps 1 through 4 were applied in the test-basin comparison study discussed in Chapter 12. The acceptance of the general level of PMP represented on these index maps was based on consideration of the Chapter 12 test-basin results, the comparison studies noted in Chapter 13, and an overall concern for reasonability relative to meteorological understanding.

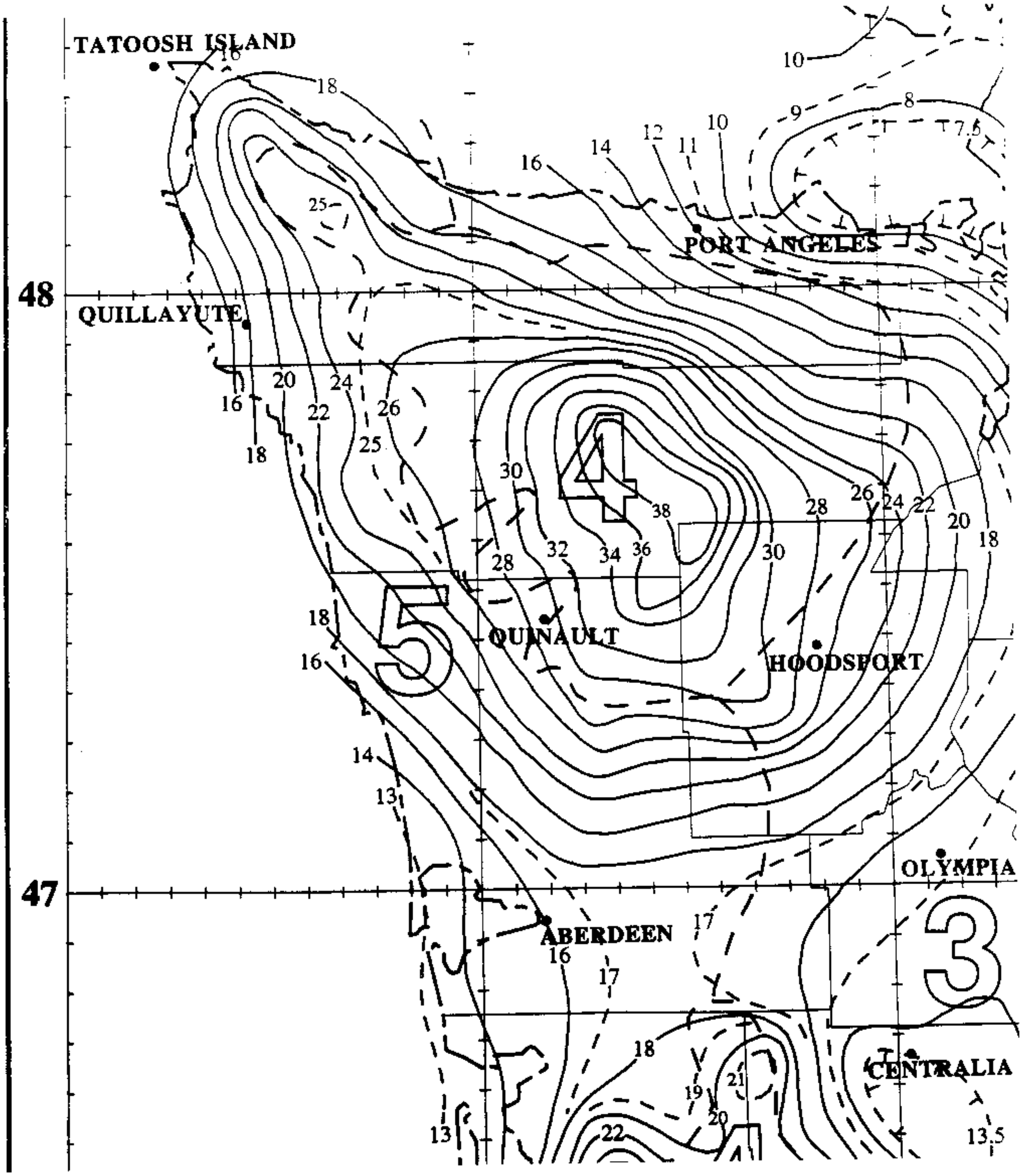

Figure 9.1.--Northwest portion of 10-mi², 24-hour general storm PMP index map. Refer to Maps 1 through 4 attached to this report for entire regional coverage.

9.1 Adjustments to the General Storm Index Map

In order to evaluate the level of total PMP shown on Maps 1-4, ratio maps (discussed in Chapter 13) were prepared comparing PMP with the 100-year, 24-hour level of precipitation from NOAA Atlas 2 (Figure 9.2). In this Figure only a portion of the total analysis is presented (reduced from its original scale) and shows the level of detail in the computer analysis based on ratios made over a 0.1-inch grid. Figure 9.3 shows a portion of the ratio analysis comparison between total PMP in this study and that from HMR 43 (also reduced from its original scale). Data from HMR 43 were readily available at only quarter-degree grid intervals, causing the isolines to take on a more jagged appearance than Figure 9.2.

Such ratio maps served as alerts to possible problem areas traceable to the methodology used in this report. The problem areas were of two types. The first involved the variability of the orographic factor K, which is brought about by the relatively fine scale of variability in the 100-year, 24-hour analyses from NOAA Atlas 2. From the comparison analysis, it was decided that troughs of lower PMP values in relatively small valleys located in orographic regions well exposed to boundary layer inflow (such as the Skagit River Valley of Washington) should be brought closer to values near the ridges. Changes of this sort were made throughout the region to reflect the understanding that moist flows could easily penetrate these valleys. The second type of problem was associated with fairly extensive areas in interior regions where lower than expected PMP to 100-year ratios were created in the preliminary analysis. Such areas were in highly orographic zones well exposed to boundary layer inflow, such as portions of British Columbia, as well as in the least orographic sections of Washington, Oregon and Idaho. In these valleys, it was believed that significant sheltering had occurred. Storms of record in, and transposable to, locations in both of these areas most likely did not have the most effective combination of mechanism and inflow wind, due to the relative isolation of these interior valleys. As such, it was reasoned that in these isolated regions, a higher than originally thought level of envelopment of the non-orographic component of PMP was warranted.

Somewhat higher than expected initial ratios of general storm PMP to 100-year precipitation and to HMR 43 values, found in western Montana and eastern Idaho, were attributed to the relatively high values of non-orographic PMP (FAFP) originally analyzed there. Initial analysis of the FAFP had placed a strong gradient of this parameter in the immediate vicinity of the Continental Divide, leaving a very relaxed gradient from eastern Washington and Oregon to the western edge of the tight gradient. This non-orographic PMP pattern was different from the gradient pattern for 100-year non-orographic precipitation. The modified analysis of non-orographic PMP brought the gradients of the two parameters into closer agreement.

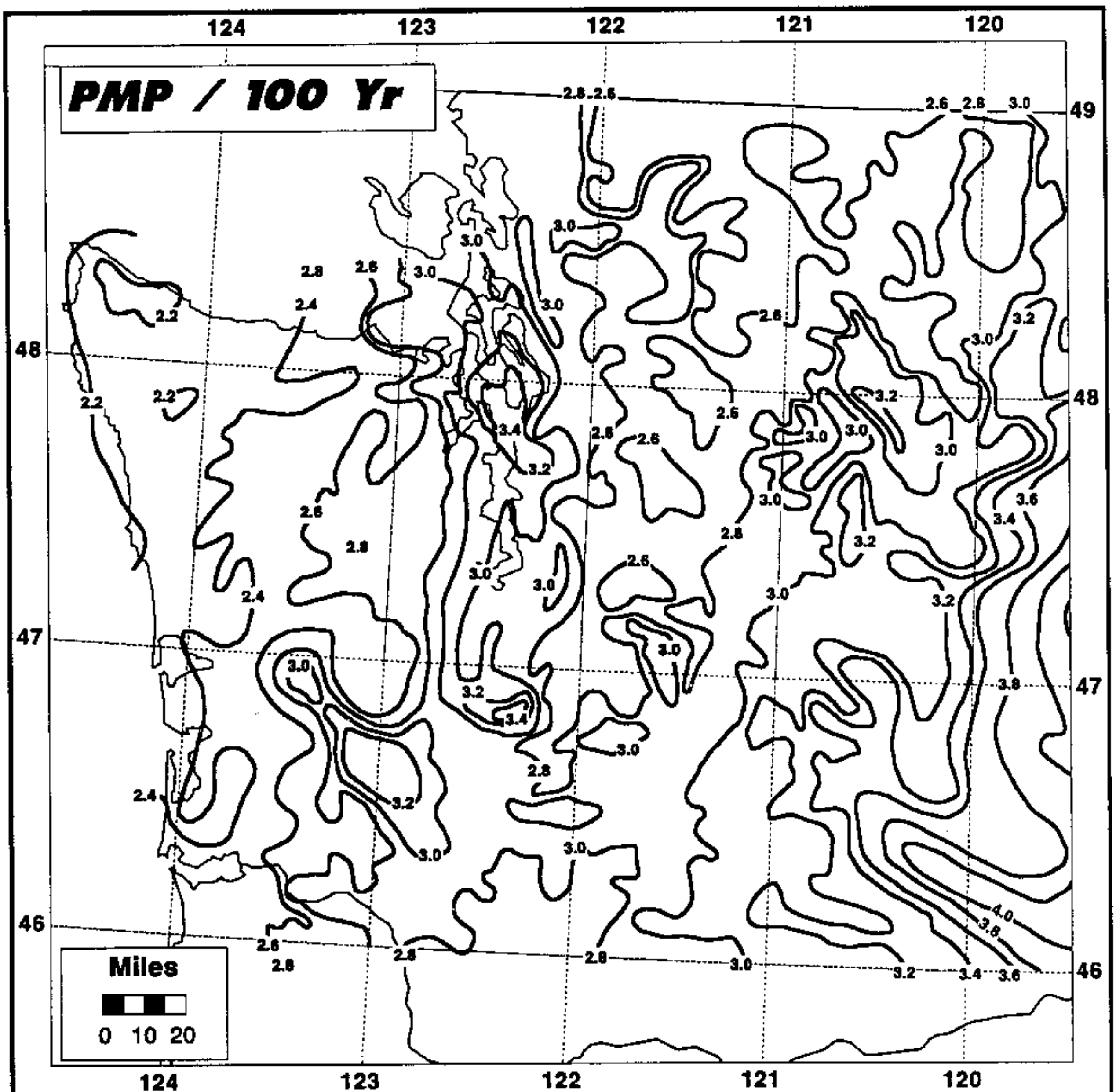

Figure 9.2.--Comparison between 10-mi², 24-hour PMP index map and 100-year, 24-hour precipitation frequency analysis from NOAA Atlas 2, non-dimensional ratios (northwest portion only).

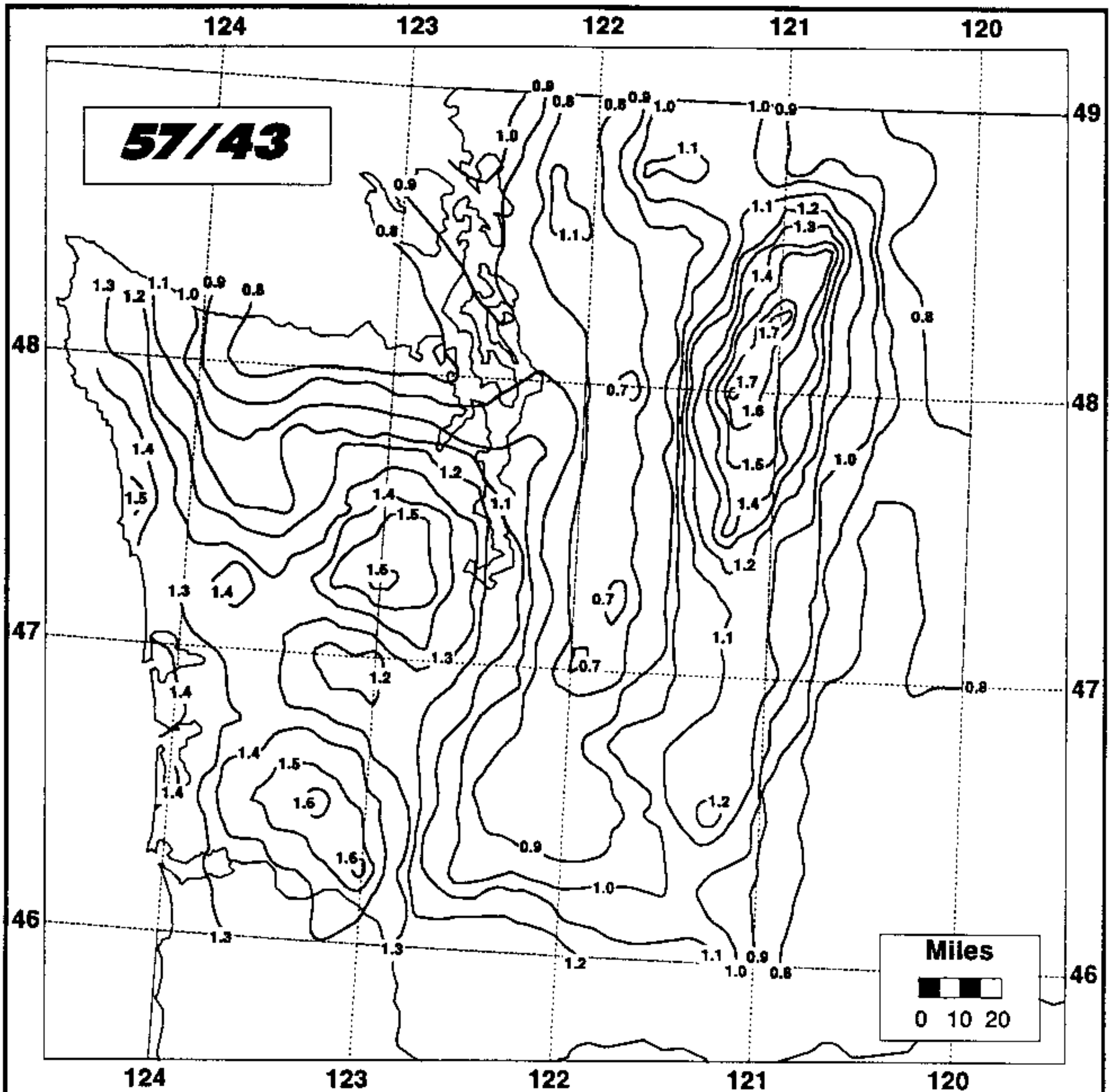

Figure 9.3.--Portion of ratio analysis between PMP estimates from this study and those from HMR 43 for 10-mi², 24 hours.

Especially in the Cascades, but also in other mountainous ranges in the study region, the computational procedure brought about a very close spatial correlation of maximum index values of total PMP and maximum values of 100-year, 24-hour precipitation. In a few instances, both the PMP and the 100-year precipitation centers were manually displaced downslope of the highest elevations in the direction of inflow associated with record-setting precipitation in that area. In these circumstances, the superposition of calculated total PMP index values and 100-year, 24-hour maxima was not changed. In some cases, especially where the maximum elevations were above 10,000 feet, the total PMP maximum was manually redrawn from its calculated location to a lower elevation, typically in the 5,000 to 9,000-foot range, in the direction of inflow moisture associated with record setting precipitation. This type of modification was brought about without making changes to either the K factors or FAFP at these locations. The implication is that an orographic factor based on 100-year data may not produce as reliable results in topographic regimes characterized by isolated steep slopes as in areas where slopes are more continuous.

It should be noted that Figures 9.2 and 9.3 are smoothed examples taken from the final ratio maps that incorporate all the adjustments discussed in this section.

9.2 Monthly Seasonal Variation of General Storm (10-mi^2, 24-hour) PMP Index Values

9.2.1 Introduction

In regions where significant winter precipitation falls as snow and therefore has a delayed runoff, it is necessary to consider other seasons than that containing the all-season PMP in order to obtain the probable maximum flood (PMF). Although the all-season PMP is thought of as being primarily rainfall brought about by an unusual set of relatively warm synoptic conditions, it says little about the surface it falls upon. In some high elevation locations in the west, particularly during late winter, there may be substantial snow accumulation on the ground. Because of this, the probable maximum flood may not occur from all-season PMP, but rather from a combination snowmelt and excessive precipitation. As a consequence, it is necessary to consider the seasonal variation of PMP to allow users to determine when the PMF is most likely for a specific basin. This section describes the way in which the seasonal variation of all-season PMP was determined.

9.2.2 Analysis

It was clear from an examination of records of maximum recorded daily precipitation amounts (by month) such as those contained in Technical Paper No. 16 (Jennings, 1952), "Maximum 24-Hour Precipitation in the United States," hereafter referenced as TP 16, that the observed maxima at many locations in the study area varied monthly and seasonally. It was also observed that the timing of seasonal maxima and the degree of month-to-month variations differed both among individual stations and among broad climatological zones within the study area.

A hypothesis was developed that governed the monthly variation of index PMP. The monthly variation would be adequately represented by a smoothed regional analysis of observed monthly record setting amounts of precipitation normalized by the largest of the 12-month records at each location. Sampling of observed values were to be from regular elevation intervals within the study area. To this end, records of daily maxima were obtained for 394 locations in the study area, 12 of which were in British Columbia.

Many of these records came from stations found in TP 16 where the period of record typically ended in 1948. Most of these and other records were then updated from climatological data through 1988. The period of record was 50 years or greater at 73 percent of these locations, 70 years or greater at 48 percent of the locations, and 80 years or more at 28 percent of the locations. Fifty-five stations had periods of record at least 90 years in length, while 11 stations had periods of record in excess of 100 years. In terms of elevation, 43 percent of the stations were below 2,000 feet; 45 percent were located between 2,000 and 5,000 feet, while the remainder were above 5,000 feet. To help determine whether there was an elevation dependency in the data among stations for a given month, or group of seasonally similar months, the locations above 2,000 feet were isolated into groups by 1,000-foot intervals.

The normalized percent (each month's amount divided by the largest amount for all 12 months or all-season amount), along with the actual record monthly amount and a symbol representing the elevation of the data, were printed on individual monthly maps across the study area. Within any given month, or group of months, and for clusters of stations having similar periods of record and within a 1,000 to 2,000 foot elevation interval, a wide range of percentages were observed. Similar percentages were observed for stations within other elevation intervals. Because of the possibility of unrepresentative storm sampling within clusters of stations, it could be argued that elevation dependency categories might apply. The preponderance of information, however, indicated that the data was not elevation-dependent for a given month. Between certain months, or seasonal groups of months, a dependency was found which was incorporated as a "principle" for analysis, as discussed below (see observation 2).

The printed maps of monthly (or seasonal) percentages were analyzed according to six principles listed below. The analysis of the monthly percentages in Figures 9.4 to 9.10 was guided by the following observations:

1. A synoptic climatology of general storms showed that the maximum percentages should be expected in winter months westward of the Cascade crest and should be expected in summer months near the easternmost portions of the study area. This variation is similar to the variation of the

maxima of mean monthly precipitation given in HMR 43 and also reported in a separate study by Legates and Willmott (1990). Minimum percentages should be expected during the opposite (i.e., summer versus winter) seasonal months at these locations. It is clearly evident from this pattern that optimum conditions for orographic enhancement and large-scale convergence forced precipitation windward of the Cascades crest occurs in the winter. Conversely, in summer months west of the Cascades, boundary layer air is stabilized by passage over the cold Pacific current. Near the eastern border of the study region, convective supplementation of large-scale convergence-forced precipitation is optimized in spring-summer months by the incursion of Gulf of Mexico moisture in the lower atmospheric layers. East of the Cascades in winter months, the persistence of continental polar air, with very low temperature and humidity, minimizes precipitation potential.

2. Between the Cascade crest and the easternmost sections of the study region, there is a tendency for rainfall maxima to be observed during the late fall or early winter at the higher elevation locations and to have a summer or early fall maximum percentage at lower elevations. Summer minima at the higher elevations in this intermountain region should also be expected. This agrees with the findings of Legates and Willmott (1990), with respect to the maxima of mean monthly precipitation.

3. Relatively large gradients of seasonal percentages are acceptable within the three broad climatological regions (west of the Cascade crests, along the Rockies and between these two) mentioned above for a given month if the lower and higher values are directly associated with major topographic features. Where little or no association exists, the highest value was considered most representative and should "prevail" within nearby clusters of lower percentage data.

4. In addition to the role played by major topographic features, the subregions controlled by an individual high percentage value may vary for a number of different reasons. These include variable lengths of record, absolute magnitude of precipitation associated with the high percentage, and station density. More control was generally given to values associated with long periods of record, large absolute depths, and low density of nearby observations.

5. Certain areas were found where exceptionally large precipitation was not measured, and it was logical that within such areas, the percentages would be relatively low for many months of the year. In such subregions, a minimum threshold level was set at 40 percent.

6. Finally, at some locations, the percentages did not conform with the conceptual models in the principles cited above. These were accepted nevertheless and "drawn for."

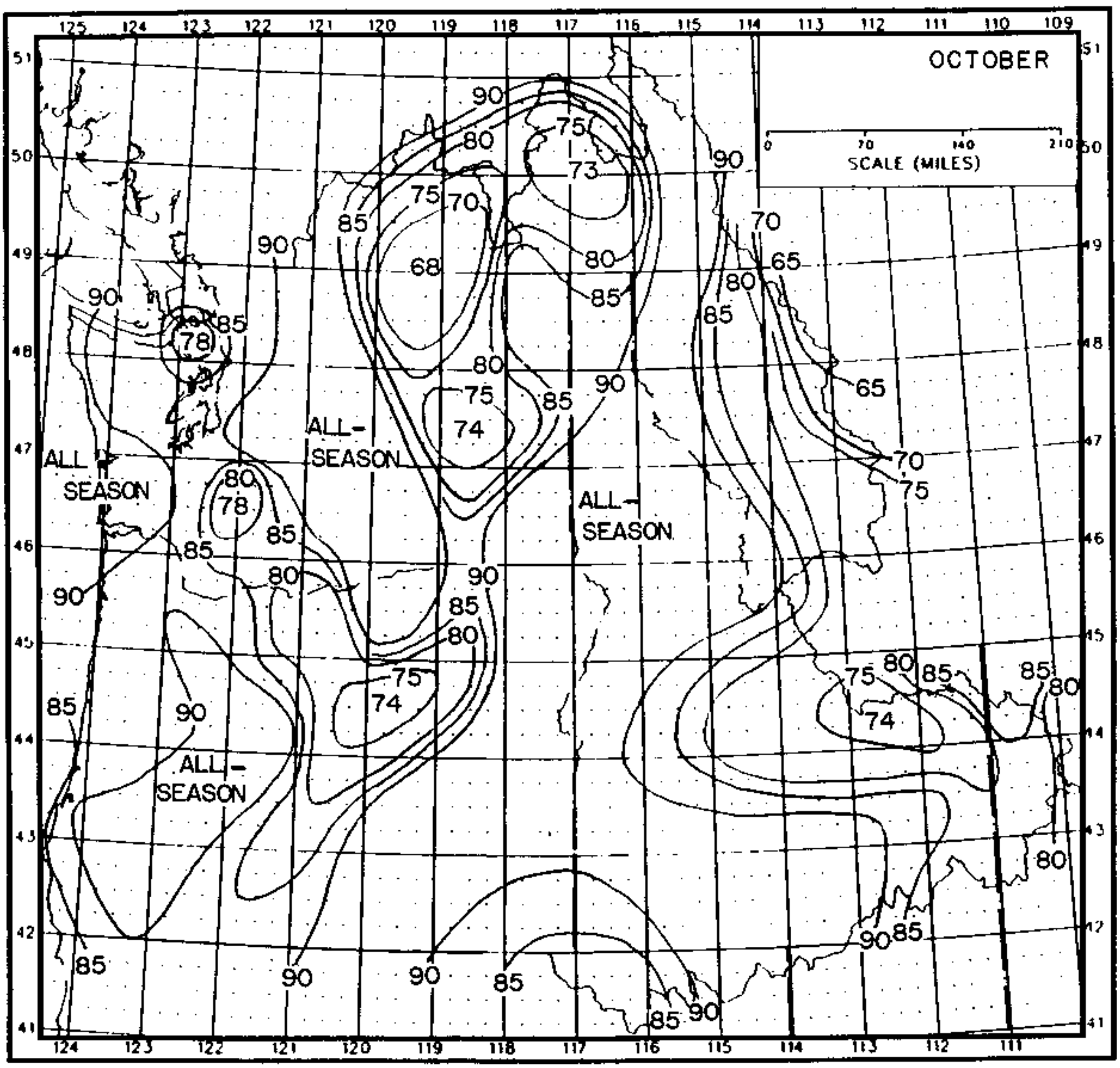

Figure 9.4.--Seasonal percentage variation of 24-hour, 10-mi², general storm PMP for October relative to all-season index maps (Maps 1-4).

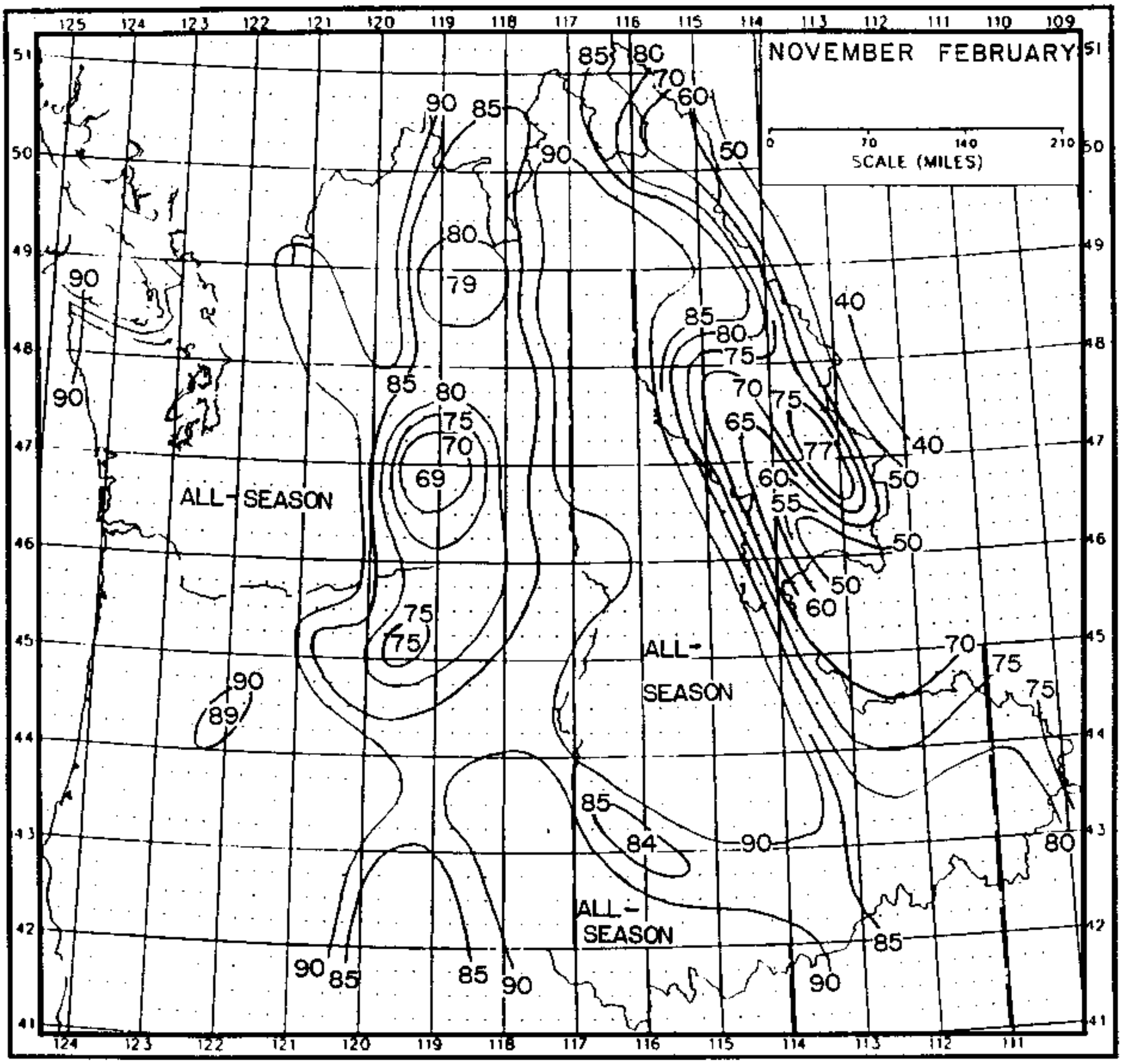

Figure 9.5.--Same as Figure 9.4 - for November through February.

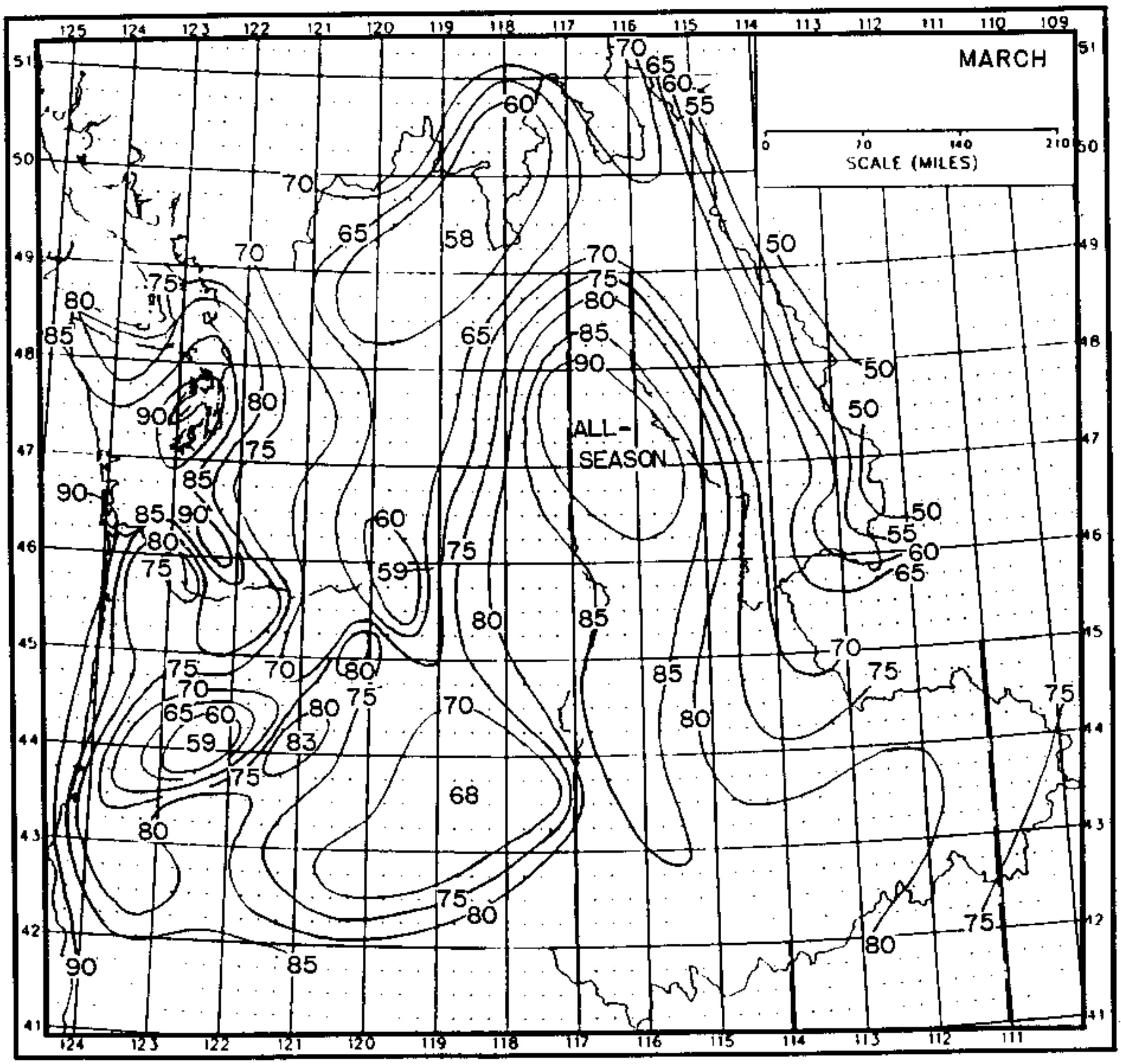

Figure 9.6.--Same as Figure 9.4 - for March.

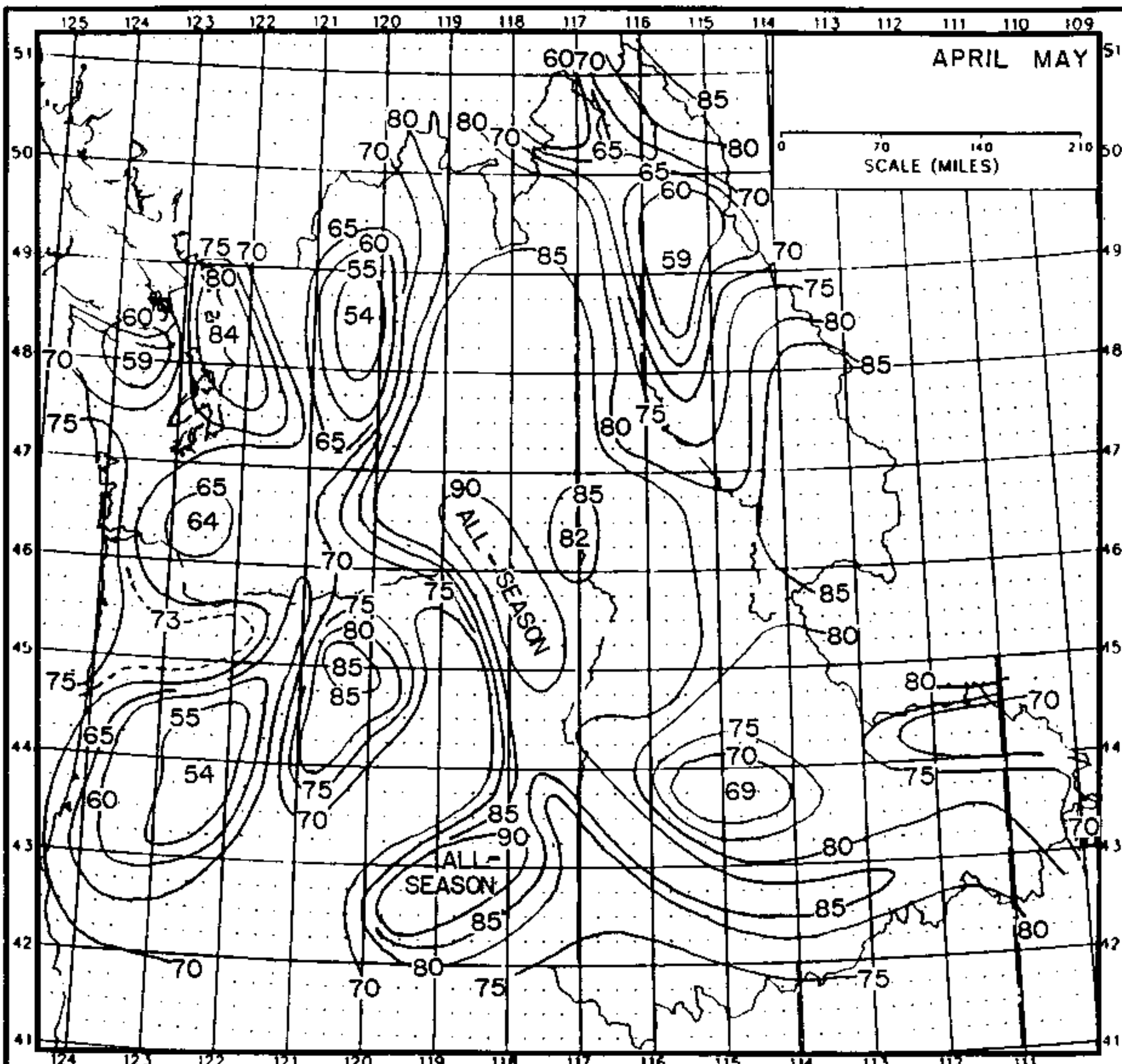

Figure 9.7.--Same as Figure 9.4 - for April through May.

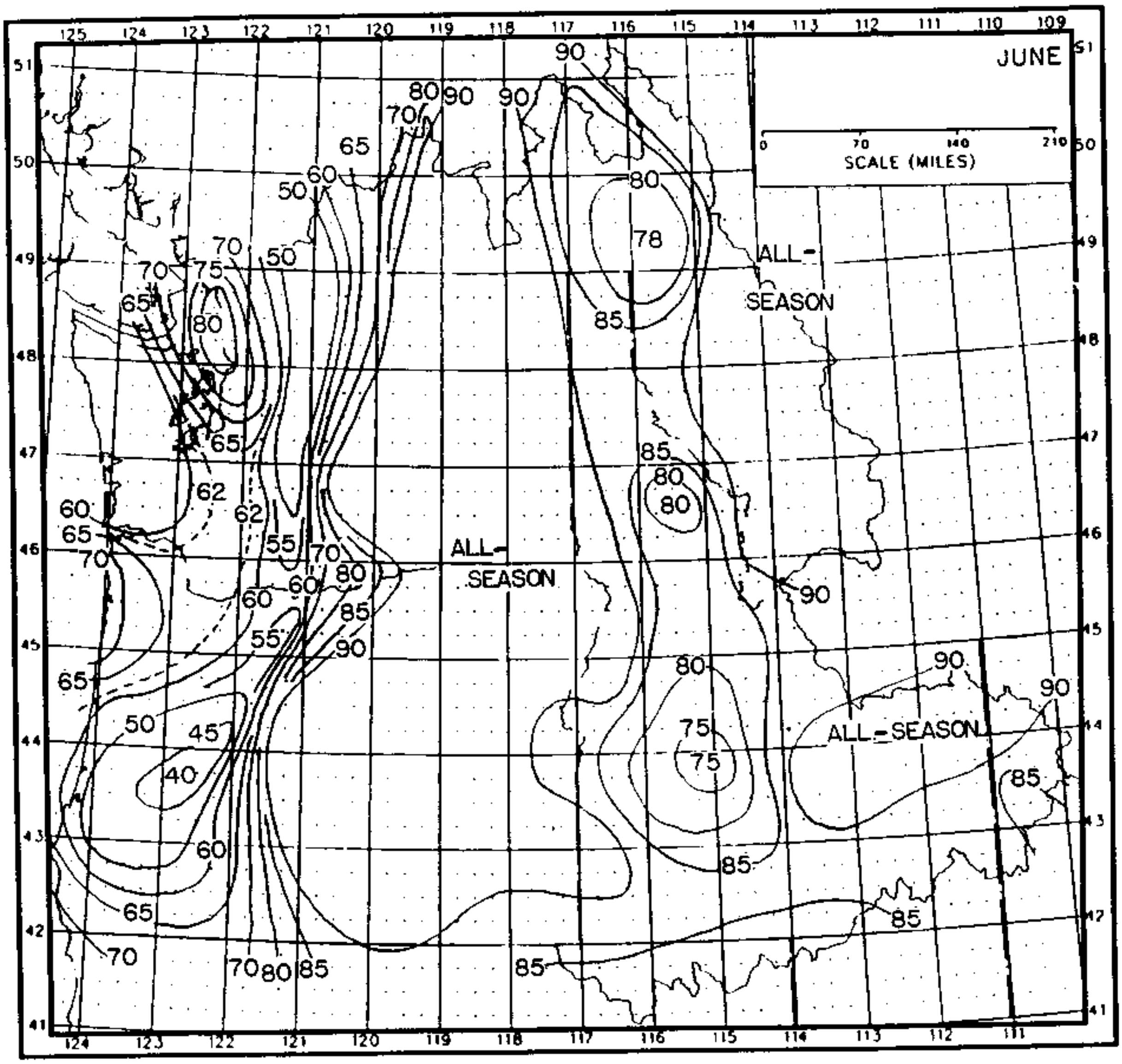

Figure 9.8.--Same as Figure 9.4 - for June.

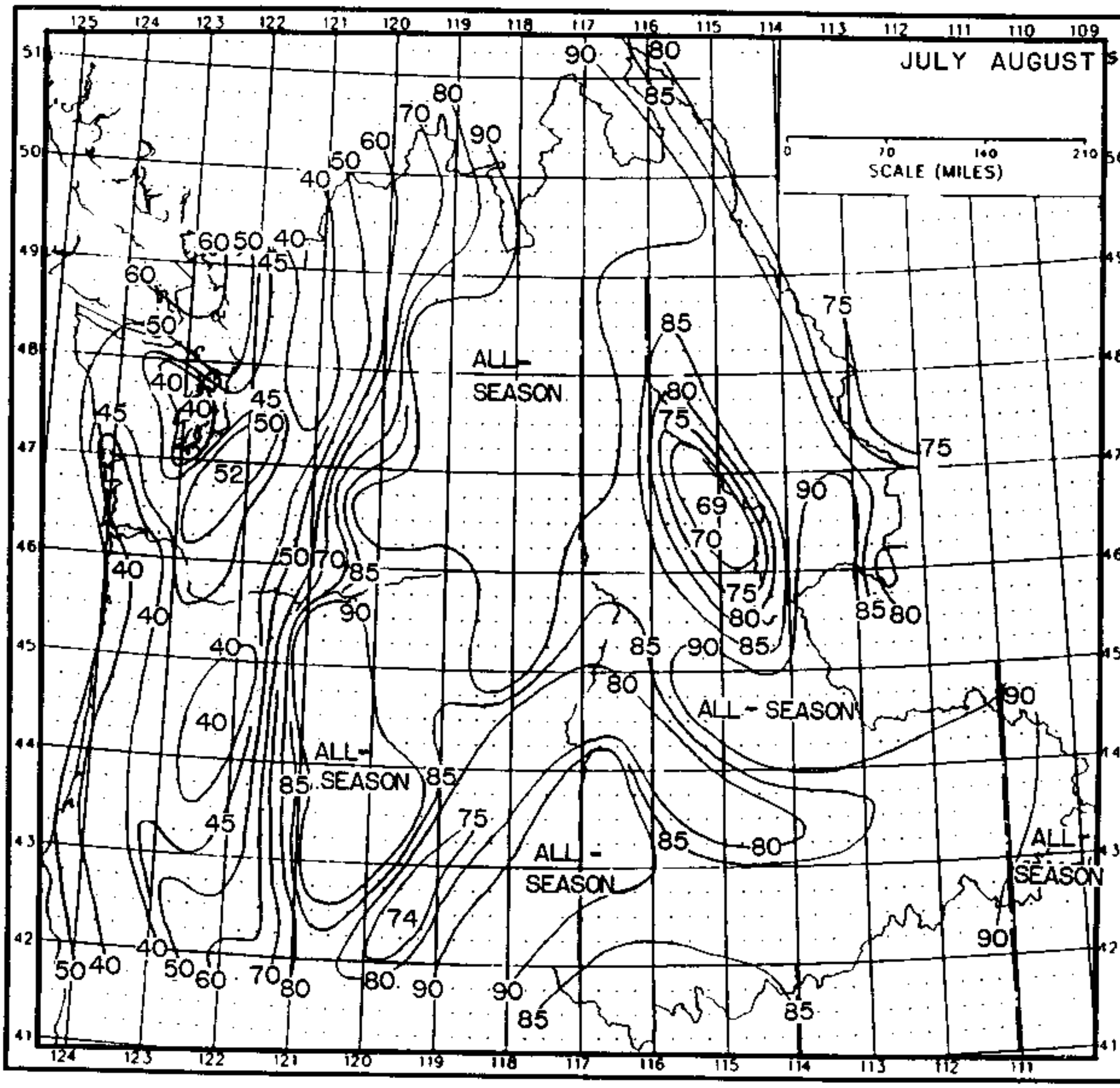

Figure 9.9.--Same as Figure 9.4 - for July through August.

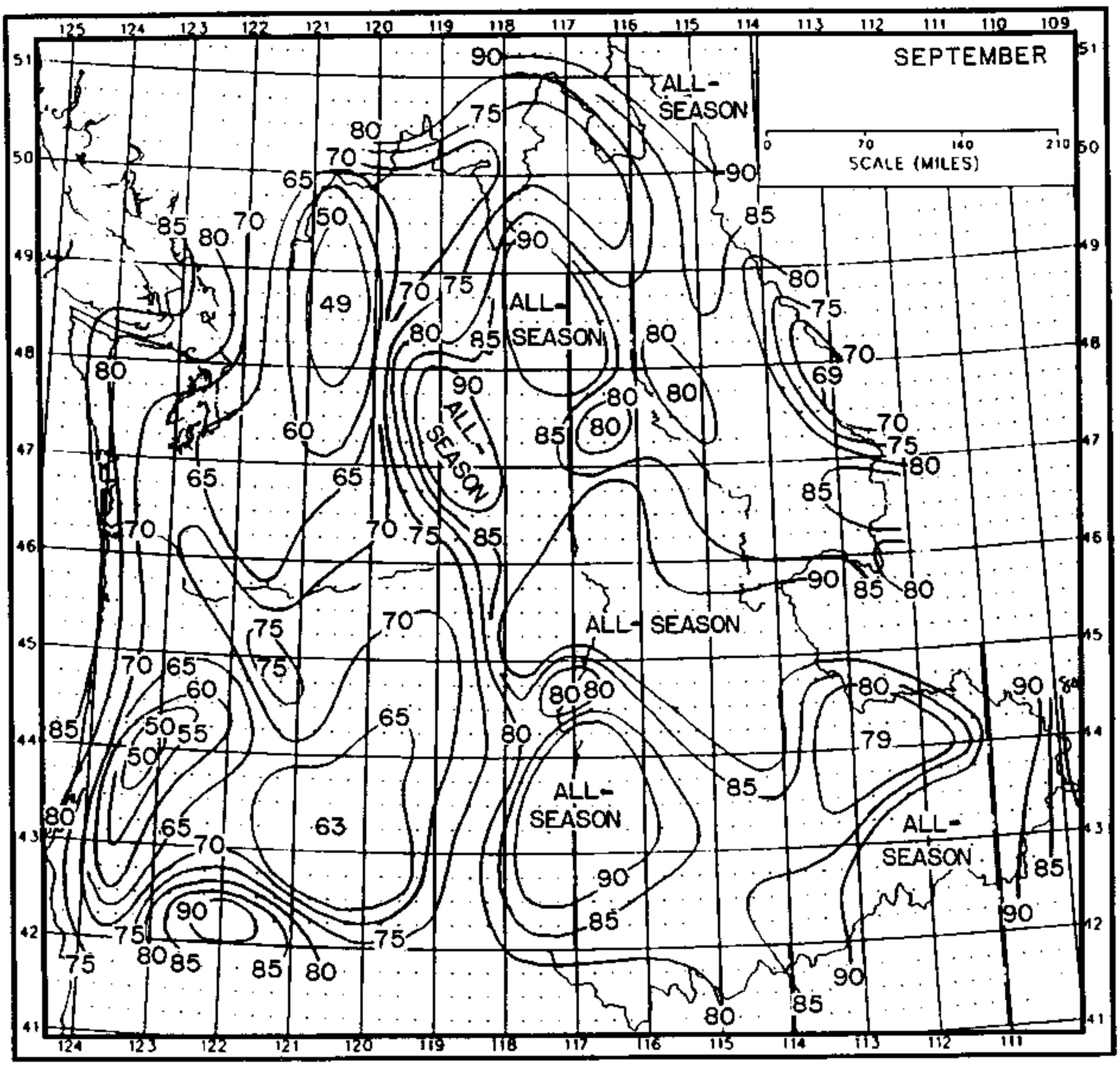

Figure 9.10.--Same as Figure 9.4 - for September.

Based on these principles, an initial analysis was accomplished for each month. Inspection of the isopercental patterns and associated values revealed similarities such that a single pattern and set of values could be used to represent more than one month. These multi-month combinations were: November through February, April and May, July and August. Thus, seven charts were drawn to depict the seasonal variation of PMP across the study region as shown in Figures 9.4 to 9.10. The scale for all seven maps is 1:8,000,000, which allows the user a relatively simple procedure to expand the scale to 1:1,000,000, the scale of the PMP index maps.

These figures show a maximum between June and August for most of the areas between 118° and 120°W. It is likely that intense local convection, occurring outside the context of general storm forcing, may have been responsible for these percentage maxima. If such were the case, these percentages would be invalid for use with an index map of general storm PMP. To investigate this possibility, a sample of twenty record setting episodes producing the maxima were reviewed for the months of June through August to determine the nature of such storms. There was insufficient information available to classify one of the older episodes, a June 1897 event. For the remaining 19 cases, four had no general storm characteristics, i.e., having both widespread, uniformly large depths of precipitation and accompanying synoptic scale convergence forcing features. Two other episodes were missing one, but not both, of these general storm characteristics.

The 13 remaining "sure" cases were believed to be sufficient to establish the likelihood that general storm forcing, with embedded intense local convection, produces maximum seasonal precipitation. From this analysis, it was concluded that PMP should also be maximized between June and August between 118° and 120°W. The synoptic context which typified many of the 13 cases of general-storm forcing, involved the boundary layer incursion of continental polar air crossing the Continental Divide from the east, accompanied by interaction with southwesterly flow aloft.

After the initial analysis was completed, percentage values at whole latitude and longitude intervals for all seven periods were extracted, plotted and examined for maxima or minima and the shape of the curve connecting the data points. Irregularities in the curves which could not be explained were eliminated by either shifting the pattern or modifying its intensity.

Figures 9.4 to 9.10 contain no percentages larger than 90. Regions where the percentages exceeded 90 have been identified as all-season for the given month or months, because it was assumed that at such places and times, the full 100-percent index level of PMP should be expected. To assure against any irregularities that may remain in Figures 9.4 to 9.10, it is recommended that, at a particular location of interest, values for all 12 months be plotted and a smooth curve drawn. Adjustments at each data point of plus or minus 5 percent may be used to help eliminate irregularities, except when an all-season value (greater than 90 percent) is indicated.

These seasonal distributions were based on daily station data, but it is assumed that these relations hold equally at other durations and areas for general storms in this region. Any deviations from these relations are suggested only when more storms have been analyzed.

10. DEPTH-AREA-DURATION RELATIONS

10.1 Introduction

Most generalized PMP studies recently produced by the NWS concentrate on the development of an index map (for one duration and area size), usually 10-mi^2 and 24 hours, based on the premise that the most reliable data are available for those dimensions. Some studies have provided index maps for a number of durations (Hansen et al., 1988), while others included selected maps for numerous durations and area sizes (Schreiner and Riedel, 1978). The choice of which presentation to follow in any particular study is based largely on the availability of data and on the need to keep the process simple. In most cases, the less information available, the simpler the process.

Most studies extend the information on index map(s) to other durations and areas by a series of depth-duration and depth-area relations. This feature is one of those that distinguishes generalized studies from site-specific studies. The latter in most cases, provide results adjusted specifically for the area and physical influences of the particular basin under consideration. In the present study for the Northwest PMP, a decision was made to develop sets of depth-area and depth-duration relations that would be tied to a single PMP index map. The index map (10-mi^2, 24 hours) has been discussed in Chapter 9. This chapter will describe the process followed to develop the depth-area-duration relations.

10.2 Depth-Area Development

10.2.1 Orographic Relations

The sets of 28 major storm[1] depth-area-duration data (Appendix 2) were taken as the data base for this effort. Experience gained in similar development for HMR 55A indicated that there may be DAD variations regionally, seasonally, and with terrain type. Thus, the storm data set was subdivided into a number of different subsets to examine such variabilities in the Northwest. An initial distinction was made by terrain type where 26 storms were judged orographic and two non-orographic. To consider regional variation, a comparison was made among averaged 24-hour depth-area data for orographic storms in three different areas; the coastal mountains (storms 32, 60, 78, 80, 88, 133, 151, 165, 175, 179), the mountains along the Continental Divide (storms 29, 155), and in the Bitterroot and Sawtooth Mountains (in western Montana and Idaho; storms 12, 82, 157, 168), as shown in Figure 10.1. For areas between 10- and 3000-mi^2, very little

[1]The Canadian storms were not included in this analysis since their DAD data was derived by procedures different from those explained in Chapter 5. They were, however, considered in the transposition of 10-mi^2, 24-hour amounts described in Chapter 7.

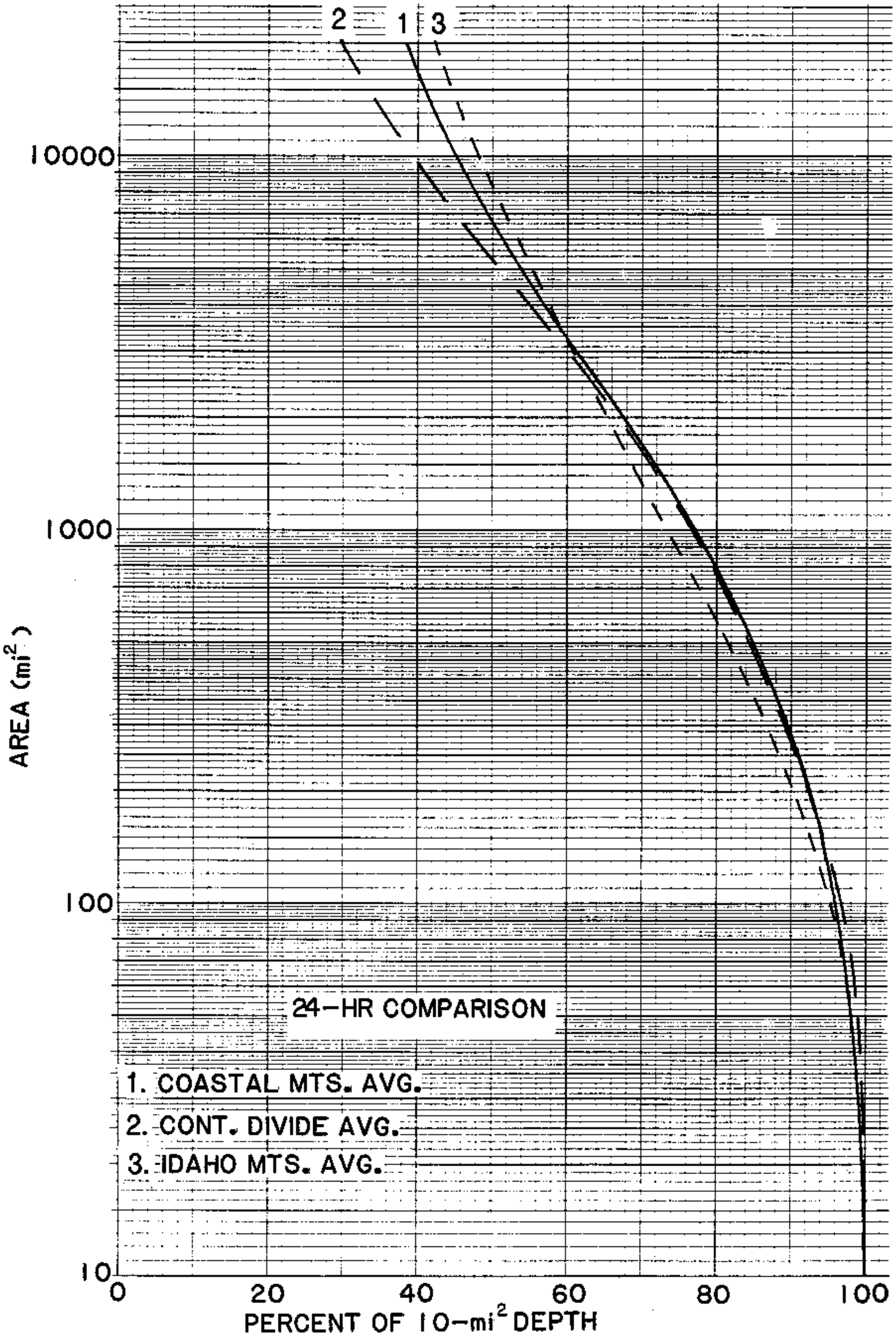

Figure 10.1.--Comparison between averaged depth-area relations at 24 hours for three orographic subsets of storm data.

variation is seen among the three average relations in this figure. Beyond 5000-mi^2, there are some differences, which may be attributable to the small storm sample involved in developing the indicated relations.

Table 10.1.--Comparison between depth-area amounts (percent of 10-mi^2 24-hour amount) for storm numbers 80 (Olympic Mountains) and 155 (Continental Divide).

	Area (mi^2)									
Storm	10	50	100	200	500	1000	2000	5000	10000	20000
80	100	97.7	94.8	91.8	85.9	81.1	70.4	51.4	40.1	31.1
155	100	97.8	95.1	90.3	83.1	77.1	70.3	56.6	44.4	33.0

Table 10.1 shows the variation between 24-hour depth-area relations for two of the more significant storms, number 80 in the Olympic Mountains and number 155 just east of the Continental Divide. The comparison is surprisingly close, even for the largest area sizes, especially in light of their geographic separation.

For all the storms (including Canadian) in Table 2.1 that occur in what has been classified as orographic terrain (Figure 3.2), nineteen storms occurred in cool-season months (November-February), three in warm-season months (June-August), and six in months considered to be transition months between these seasons (March-May and September-October). The seasonality of the storms was used to aid in the development of realistic depth-area relations for this study, several groups of storm data were averaged. The Canadian storm data were not included in these averages, however, because of differences between Canadian procedures and those used in this study to obtain depth-area-duration data. Numerous comparisons were made in an attempt to discern significant differences among the 28 United States storms. Based on a number of comparisons of various subregional, seasonal, durational and terrain-related averages, it was concluded that an orographic storm average from 18 cool-season U.S. events provided the most reliable orographic depth-area relations for the entire region. The 18-storm average was smoothed to obtain the relations shown in Figure 10.2. The depth-area relations in Figure 10.2 represent all orographic regions in the Northwest region regardless of season, as supported by the similarity between the major winter storm (80) and summer storm (155) curves shown in Table 10.1.

Table 10.2 provides the tabular average values for the curves given in Figure 10.2. A comparison of these new results to values taken from HMR 43 and HMR 55A for selected areas and durations is given in Table 10.3. The HMR 57 curves are based on the 18-storm average of orographic cool-season storms, while those for HMR 43 are based on averages of computations taken near the same 18 orographic storm centers. The HMR 55A results came from the orographic "A"

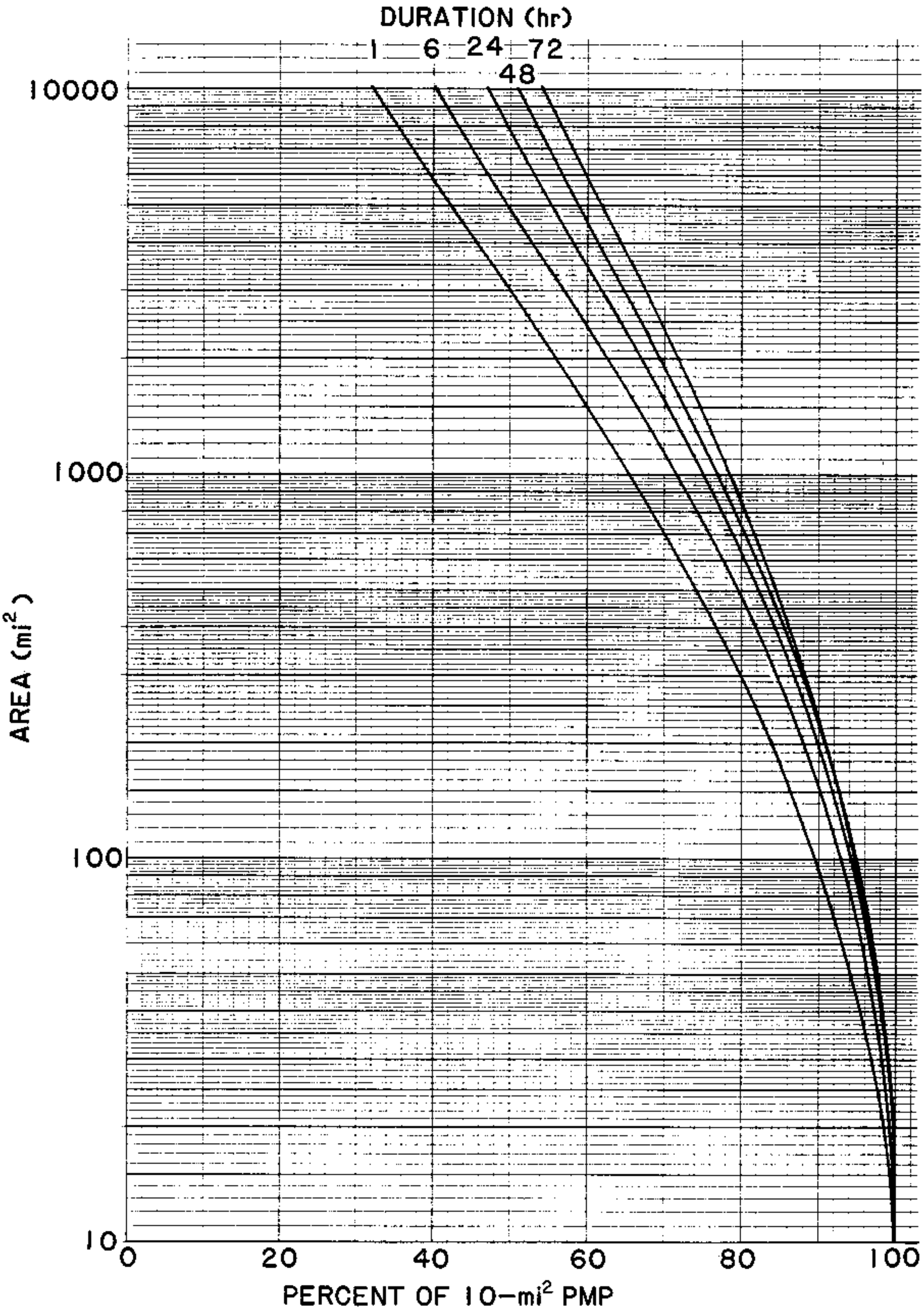

Figure 10.2.--Depth-area relations adopted for orographic subregions based on averages of 18 cool season United States storms.

curves (Figure 11.9 from that report), and represent intense summer (June) storms for that region.

Table 10.2.--Adopted orographic depth-area values (Figure 10.2) for present Northwest PMP Study, based on averages of 18 storms (percent of 10-mi² PMP).									
Duration (Hours)	Area (mi²)								
	10	50	100	200	500	1000	2000	5000	10000
1	100	94.2	89.5	84.0	74.2	65.5	56.0	42.2	32.2
6	100	96.5	93.0	88.1	79.8	71.8	62.7	49.7	40.2
24	100	97.3	94.3	90.1	82.3	75.1	67.0	55.3	47.0
48	100	97.7	94.8	90.7	83.6	77.2	69.7	59.0	51.0
72	100	97.8	95.2	91.2	84.6	78.8	71.9	62.0	54.3

The variation in the depth-area curves (Table 10.3) among the three reports is less as the duration increases, (especially for areas of 1000-mi² or less). Also for the larger areas, the HMR 57 depth-area relations approach the HMR 55A results by falling off more rapidly than did HMR 43. Therefore, one of the significant differences of the current storm data analysis is that for larger areas (greater than 1000-mi²), the new results are likely to be lower than in HMR 43 for comparable durations and index values. The available data indicates that there is no seasonal variation in depth-area relations for orographic regions in the Northwest.

Table 10.3.--Comparison (in percent of 10-mi² amount) of orographic depth-area relations for three reports (HMRs 43, 55A and 57).												
	Duration (Hours) 6 Hours				24 Hours				72 Hours			
	Area (mi²)				Area (mi²)				Area (mi²)			
Report	10	200	1000	5000	10	200	1000	5000	10	200	1000	5000
HMR 57	100	88.1	71.8	49.7	100	90.0	75.1	55.3	100	91.2	78.8	62.0
HMR 43	100	82.8	69.3	54.3	100	88.0	78.3	67.5	100	90.0	81.6	71.9
HMR 55A	100	79.8	62.5	44.0	100	87.0	74.0	58.0	100	90.5	79.1	64.9

10.2.2 Least-Orographic Relations

As a comparison to the orographic relations of Figure 10.2, a set of depth-area relations was developed for the least-orographic regions in this study. The data sample in Table 2.1 was very sparse; only two storms were identified as non-orographic (106, 143). Figure 10.3 shows average relations based on these two storms and indicates little to no durational variation for areas less than 500-mi^2, an unusual situation. For comparison, a set of non-orographic curves was taken from HMR 51 for a representative location at 47°N, 101°W (the 1-hour curve came from HMR 52), and are shown in Figure 10.4. The shape and distribution of curves in Figure 10.4 are more typical of extreme storm data and do not agree well with those of Figure 10.3.

A number of alternative depth-area relations were examined using different data sets. The solution that was adopted for this study is shown in Figure 10.5, and results from an average of the orographic results in Figure 10.2 and the HMR 51 results from Figure 10.4. The adopted results in Figure 10.5 are compared with depth-area computations from HMR 43 (Table 10.4) for locations in least-orographic regions (areas limited to 1000-mi^2 or less in that report). Table 10.4 shows the adopted HMR 57 least orographic relations are somewhat in agreement with HMR 43 results for the smaller areas (less than 200-mi^2), and they decline more rapidly (except at 6 hours) as area increases. The two-storm depth-area averages (Figure 10.3) are compared with the adopted relations (Figure 10.5) in Table 10.5. The only agreement between the two-storm averages and the adopted depth-area relations are for areas of 5000-mi^2 or greater and for a 6-hour duration. The adopted curves at all durations drop off more rapidly than is shown by the two-storm least-orographic data.

10.3 Depth-Duration Development

10.3.1 Storm Sample Approach

Initially, regional comparisons were made for depth-duration relations in a manner similar to what was done for the depth-area development. At 10-mi^2, Table 10.6 shows this comparison for the orographic storms used in Figure 10.1. The values in parentheses indicate averages are based on three-storms or less (not all storms had 48- and 72-hour durations). The results shown in Table 10.6 suggest that there is some regional variation in depth-duration relations, particularly between the Continental Divide and elsewhere, for durations beyond 24 hours.

Table 10.7 shows a comparison between the 18-storm winter orographic averages and the two-storm least-orographic average for durations of 24 hours and less (the least-orographic storms, 106 and 143, only lasted 24 hours). No long-duration least-orographic storms were available in the storm sample, but it is possible that storms over least-orographic regions are typically of shorter duration than orographic storms. The results in Table 10.7 show considerable disparity between the depth-duration relations for the two terrain-types, but as with the depth-area comparison, the two-storm average may not provide representative results. A meteorological rationale for these results may be because least-orographic storms would exhibit greater convection (higher 6/24-hour ratios) than orographic storms, especially since the former occurred during the warm season.

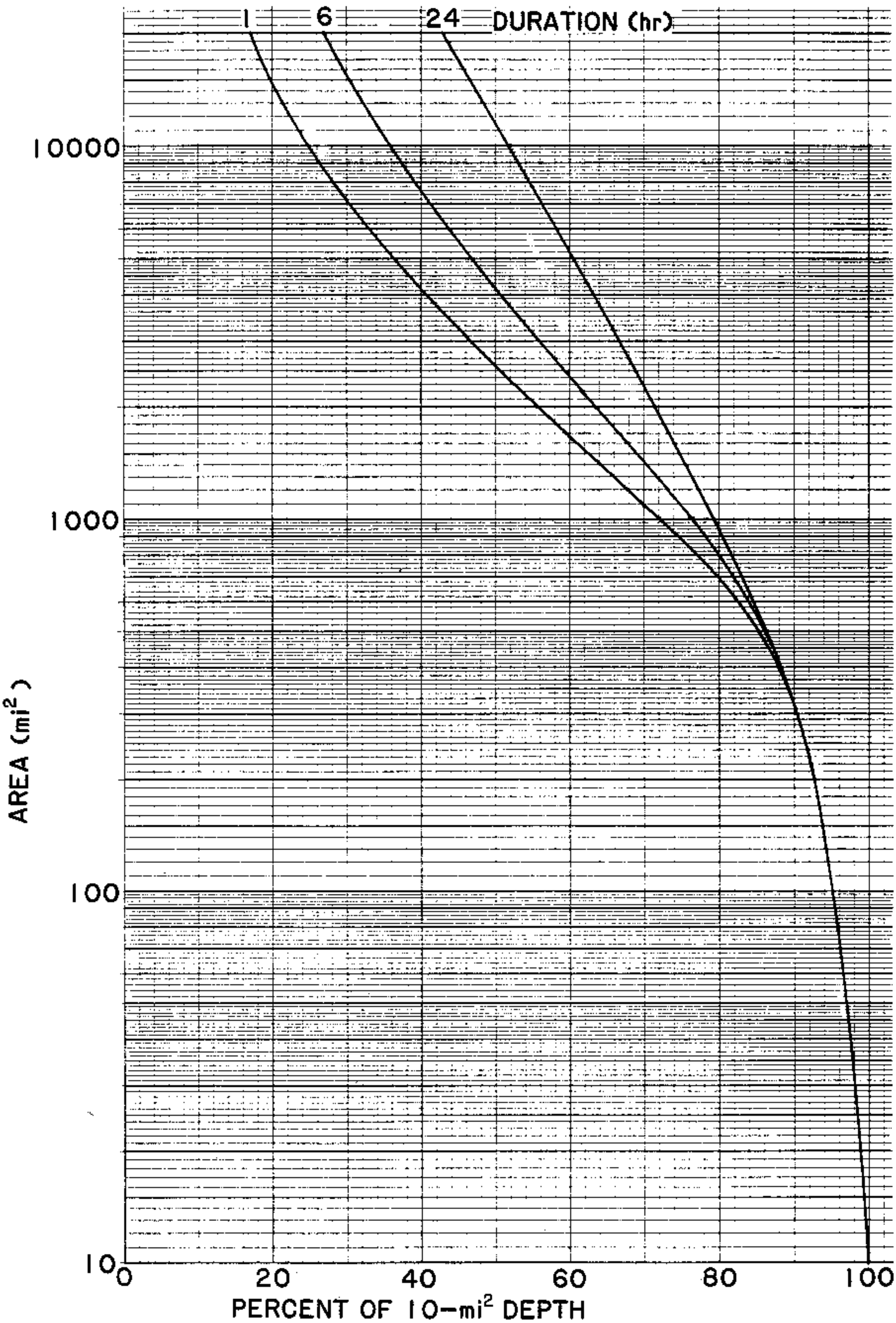

Figure 10.3.--Depth-area relations based on average of two storms (106 and 143). Not adopted for least orographic subregions in this study.

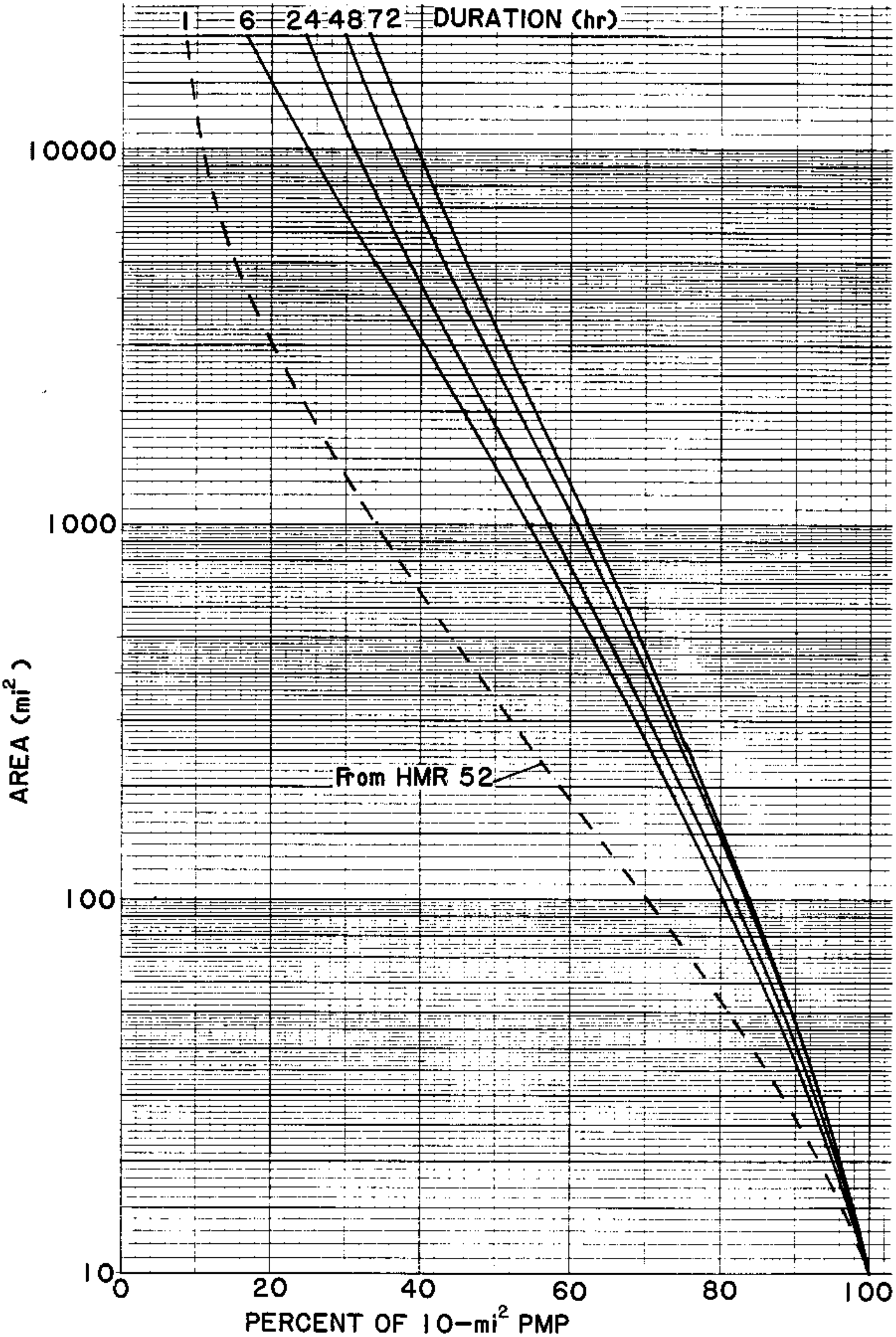

Figure 10.4.--Depth-area relations for least-orographic conditions at 47°N 101°W from HMR 51 (1978). Dashed curve from HMR 52 (1982).

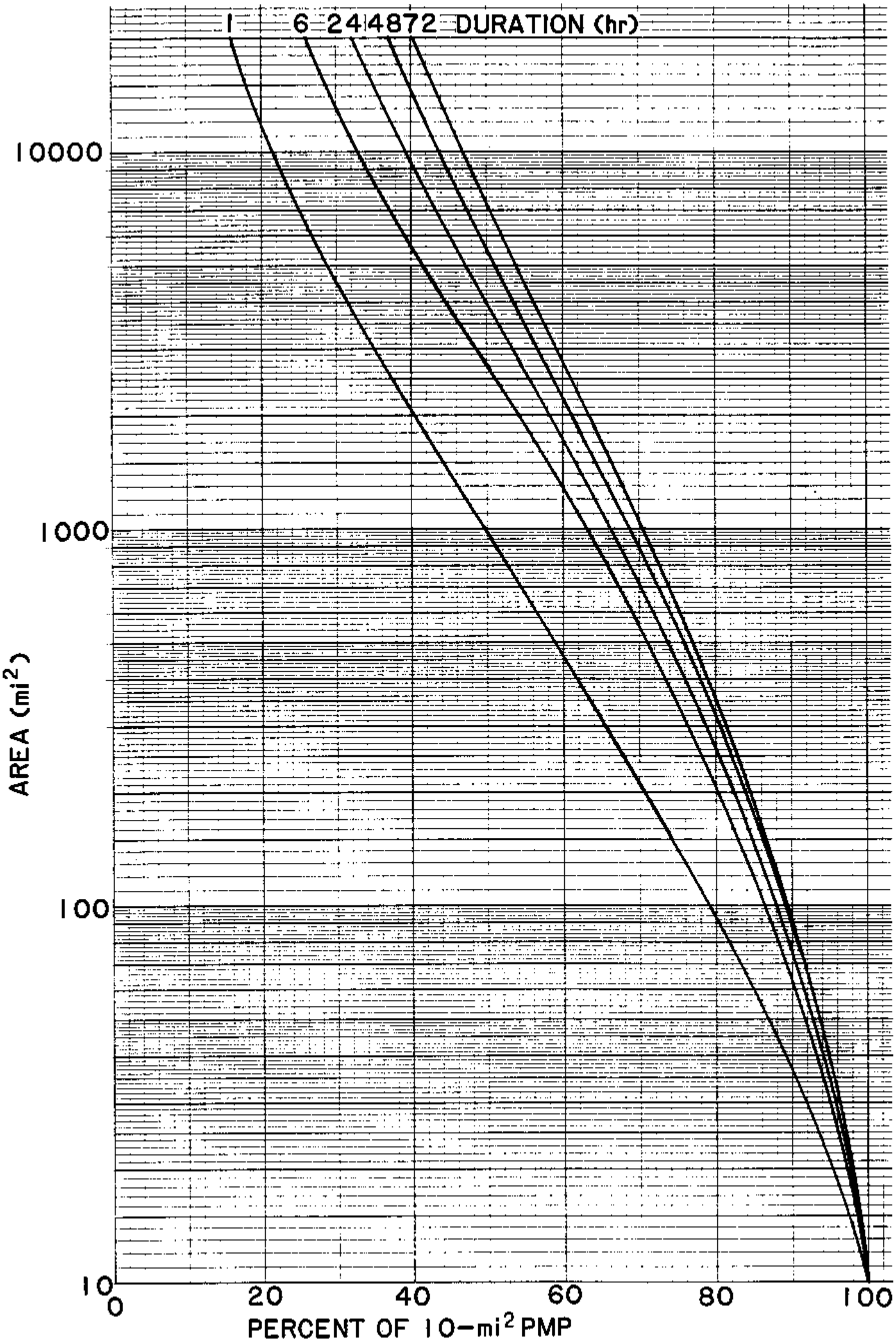

Figure 10.5.--Depth-area relations adopted for least orographic subregion (Average of Figure 10.2 and Figure 10.4).

Table 10.4.--Comparison of least orographic depth-area relations (in percent of 10-mi² amount) between HMR 57 (Figure 10.5) and least-orographic locations in HMR 43.

	(Area mi²)		
Report	10	200	1000
6 hours HMR 57	100	80.4	63.9
6 hours HMR 43	100	77.5	62.5
24 hours HMR 57	100	82.5	66.8
24 hours HMR 43	100	84.7	73.8
72 hours HMR 57	100	84.6	70.9
72 hours HMR 43	100	88.0	79.0

Table 10.5.--Comparison of adopted least-orographic depth-area relations with average from storm 106 and storm 143.

	Area (mi²)					
Report	10	200	1000	2000	5000	10000
6 hours HMR 57	100	80.4	63.9	54.4	41.6	32.4
6 hours two-storm average	100	92.6	76.2	63.0	46.7	36.0
24 hours HMR 57	100	82.5	66.8	58.2	47.2	39.3
24 hours two-storm average	100	92.6	79.2	71.3	60.5	51.8
72 hours HMR 57	100	84.6	70.9	63.4	54.0	46.9
72 hours two-storm average	100	92.6	79.4	72.2	61.9	54.0

10.3.2 Adopted Depth-Duration Approach

The evidence in Tables 10.6 and 10.7 indicates that there is some basis for variation in depth-duration relations across the Pacific Northwest, in contrast to the case for depth-area relations. Several alternative solutions to develop reliable depth-duration relations across the region were considered. The alternative that offered the most reasonable solution was adapted from the work of Schaefer (1989), who studied extreme precipitation events for the State of Washington.

This study accepted the separation of terrain classes for the State of Washington given by NOAA Atlas 2. Another subdivision to represent the coastal lowlands was added, based on a comparison of mean annual precipitation data (ranges and means). Based on this regional classification, Schaefer established sets of depth-duration relations (percent of 24-hour amount) for various exceedance probabilities for each terrain class and for three levels of "kernel" values (2, 6 and 48 hours). The kernel in these tables represents the duration of the major precipitation that fell in the events considered, somewhat similar to the core precipitation concept used in storm separation (see Chapter 8).

Table 10.6.--Comparison of 10-mi² depth-duration values (percent of 24-hour amount) for orographic storms used in Figure 10.1 (<3 storm average).

	Duration (Hours)							
Location	1	6	12	24	36	48	60	72
W. Coastal Mt. Average	11.6	41.7	63.5	100.0	128.0	150.1	176.2	192.3
Idaho Mt. Average	13.5	47.0	67.1	100.0	125.6	156.7	(168.8)	(183.9)
Contin. Divide Avg.	(12.0)	(44.8)	(72.2)	(100.0)	(110.0)	(115.6)	(126.3)	(126.3)

Table 10.7.--Comparison between orographic and least-orographic depth-duration relations (percent of 24-hour amounts). Same storms used in Tables 10.2 and 10.4.

	Duration (Hours)			
	1	6	12	24
Orographic average	12.3	40.9	61.8	100.0
Two-storm least-orographic average	19.7	60.8	80.3	100.0

Schaefer's subdivisions were extended in this study to cover the entire Northwest region, while including the subregions used in NOAA Atlas 2 (Figure 10.6). The numbers in that figure identify the subregions used in NOAA Atlas 2. Using Figure 10.6 as a starting point and Schaefer's adaptation for the State of Washington, a modified subregional breakdown was developed as shown in Figure 10.7. The modifications include a narrow coastal lowland (Zone 5), a narrow zone along the west slopes of the Rocky Mountains (Zone 6), and extensions of subregional boundaries into southern British Columbia. Table 10.8 identifies the subregions shown in Figure 10.7. The same subregional boundaries in Figure 10.7 are also shown as the dashed blue lines on the PMP index maps (Maps 1-4) attached to this report.

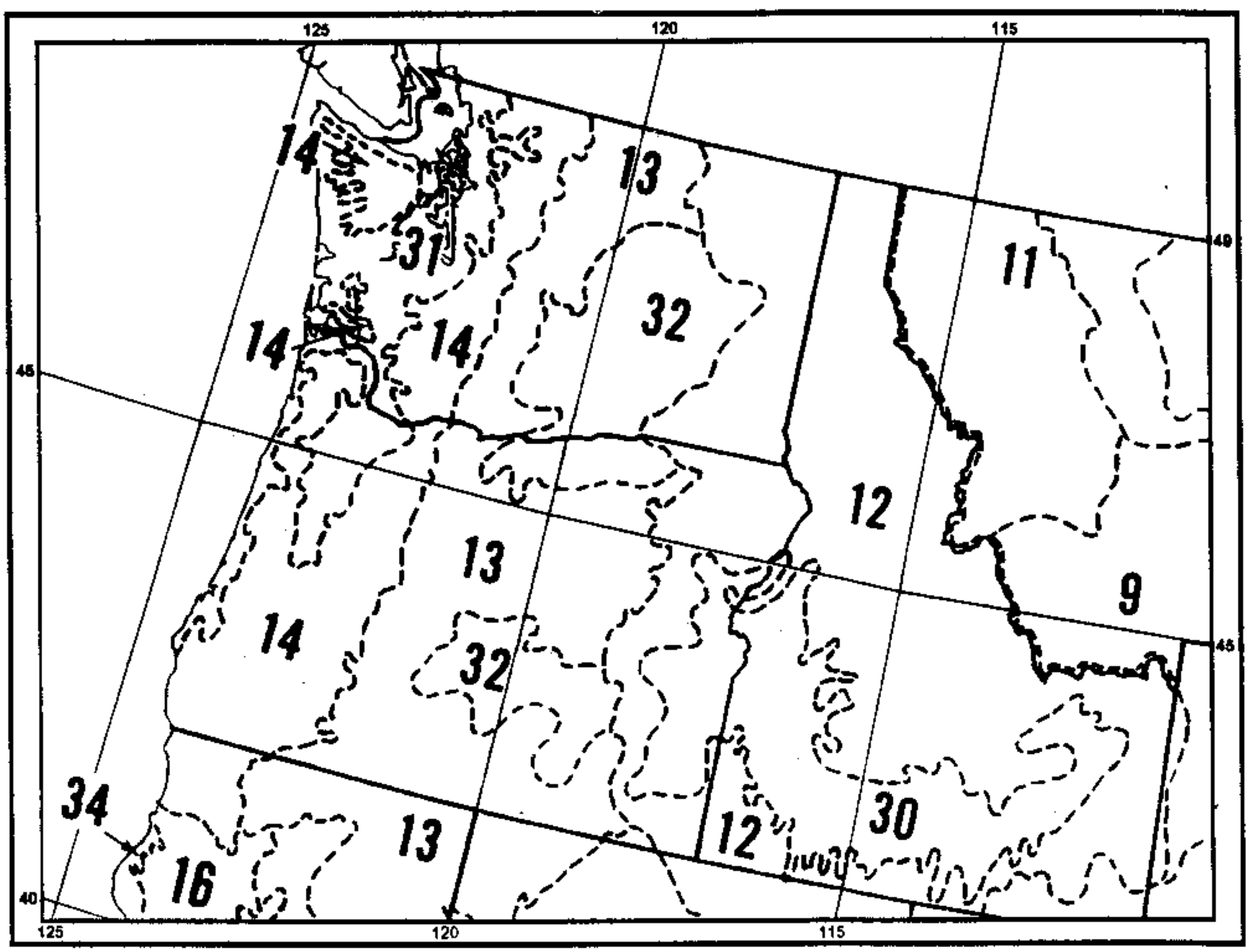

Figure 10.6.--Climatological subregions identified in NOAA Atlas 2 (1973). Least orographic subregions are 30, 31 and 32; others are orographic.

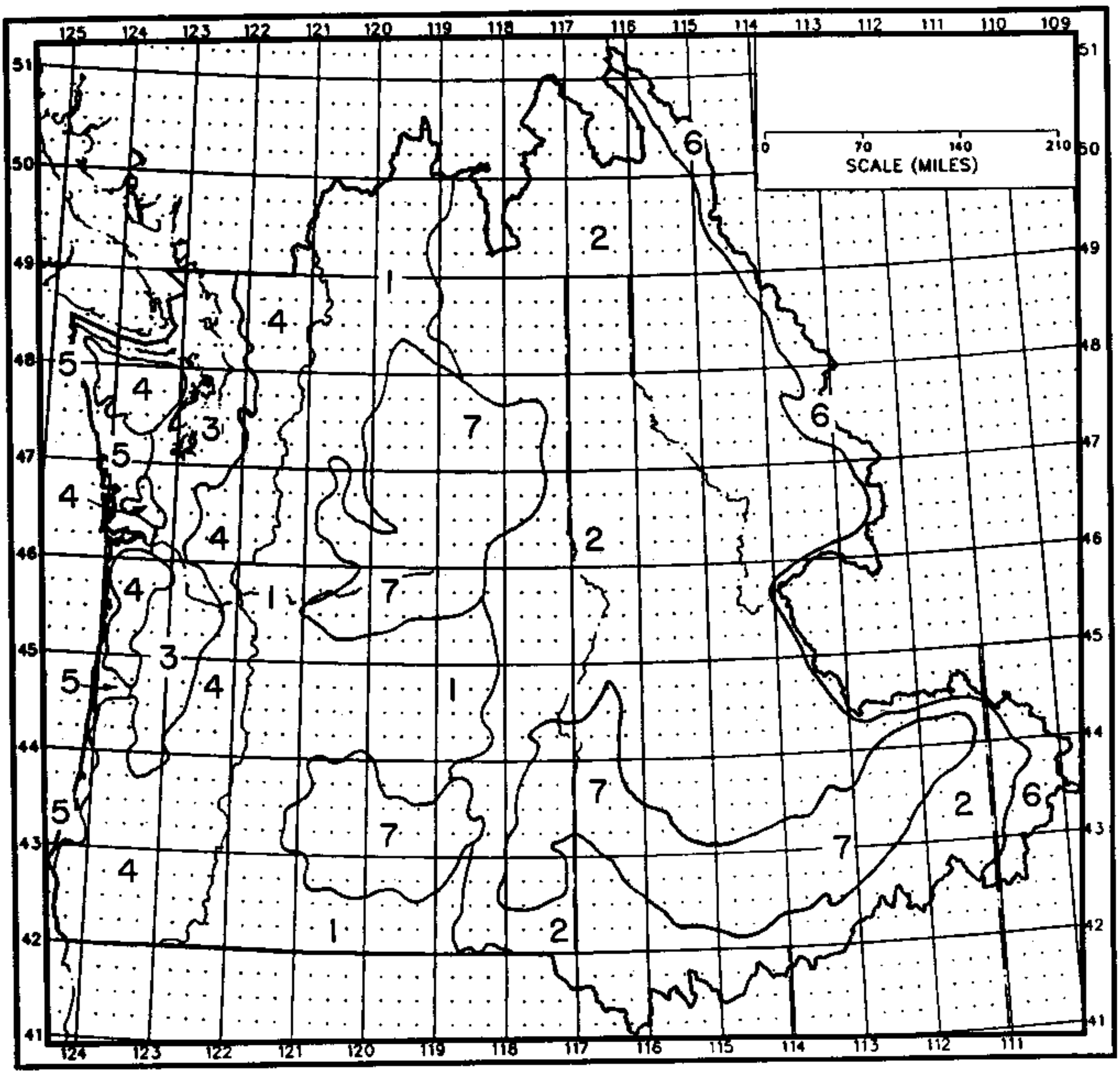

Figure 10.7.--Subregions adopted for this study.

Table 10.8.--Subregions used in this report to assist in depth-duration analysis.	
Subregion	Identification
1	East of Cascades ridge to 118-119°W as noted - orographic
2	East of 119°W to west slopes of the Rockies - orographic
3	Least orographic (west of Cascades)
4	West of Cascades - orographic
5	West of Cascades - coastal orographic
6	West slopes of the Rockies - orographic
7	Least orographic - east of Cascades

In the present study, the greatest number of storms in Table 2.1 occur in subregion 4, the orographic region west of the Cascade ridgeline. There are 15 storms from November to January in this subregion and their average depths in percent of 24-hour amount are:

	Duration (Hours)						
	1	6	24	36	48	60	72
(%)	11.5	39.9	100.0	128.8	149.2	174.2	192.2

Schaefer presented results in the form of probabilistic depth-duration curves as in Table 10.9, which contains results for 24-hour extreme storms in the mountains of western Washington. In looking at Table 10.9, it is necessary to describe how it was used to support the present study. It was suggested by Schaefer (personal communication) that 48-hour kernel values should apply only for durations from 24 hours to 72 hours and, for durations shorter than 24 hours, ordinate values for the 6-hour kernel should be used. Combining this information and comparing it to the 15-storm orographic average depth-duration data, it was determined that the closest match occurred for an exceedance probability of about 0.15, i.e., in only 15% of the storms do the depth-duration curves exceed those values. The match was poorest beyond durations of 48 hours. After numerous trials, the 15 percent exceedance probability was adopted for this study rather than a more rare level and is an attempt to impose a degree of conservatism on the final result.

A decision was made to extend Schaefer's results for regions 1, 3, 4, 5 and 7 for the entire HMR 57 study area. Table 10.10, which is separated into subregions east and west of the Cascade ridgeline, presents these depth-duration curves. These were only minor variations from Schaefer's curves in the period between 12 and 48 hours. Table 10.10 also includes depth-duration data for subregions 2 and 6, which were not delineated by Schaefer. Evidence from the storm data indicated that storms centered farther east from the Cascades, had a flatter temporal distribution of the depth-duration curve at longer durations. Subregion 2 accounts for this somewhat lower-tailed distribution of rainfall for durations beyond 24 hours.

Subregion 6, representing the western slopes of the Rocky Mountains, was also added to Figure 10.7. As shown in the table of adopted depth-duration curves (Table 10.10), this region has values intermediate to subregions 2 and 7. These values fit the observation that the most intense rainfall in the Rockies comes from warm-season (May-October) storms, whereas curves in subregion 2 and 7 were developed primarily using data from cool-season storms. Note that the ratios show storms in orographic regions (Zone 6) have more gradual curves at shorter durations and steeper curves at longer durations vis-a-vis storms in least orographic regions (Zone 7).

Table 10.9.--Dimensionless depth-duration curves for 24-hour extreme storms in Western Washington for 48-hour kernels and selected exceedance probabilities (Schaefer, 1989).

	Duration (Hours)											
Exceedance probability for kernel	0.5	1.0	2.0	3.0	6.0	12.0	18.0	24.0	36.0	48.0	60.0	72.0
.95	.052	.084	.146	.205	.362	.631	.841	1.00	1.021	1.040	1.071	1.108
.90	.051	.084	.146	.205	.361	.629	.839	1.00	1.035	1.069	1.103	1.147
.80	.051	.084	.145	.204	.360	.625	.836	1.00	1.060	1.113	1.163	1.217
.67	.050	.083	.144	.203	.358	.621	.832	1.00	1.100	1.173	1.239	1.305
.50	.050	.082	.143	.201	.356	.614	.826	1.00	1.162	1.252	1.338	1.421
.33	.050	.081	.142	.200	.353	.607	.820	1.00	1.214	1.344	1.455	1.557
.20	.048	.081	.141	.198	.350	.600	.813	1.00	1.267	1.440	1.575	1.697
.10	.048	.080	.140	.197	.348	.591	.805	1.00	1.326	1.544	1.706	1.851
.05	.048	.079	.139	.195	.345	.585	.799	1.00	1.372	1.627	1.811	1.974

Comparing the depth-duration data from storms in Table 2.1, with the information given in Table 10.10, did show some agreement. The results of a comparison are shown in Table 10.11 for two of the subregions, 2 and 7. For subregion 2, the orographic area east of 119°W, the adopted depth-duration values are compared with data for three cool-season storms (12, 157, and 168). Even better agreement occurs in subregion 7, the least orographic area east of the Cascades, between the two least orographic storms (106 and 143) and the adopted relations. Should there be a need for intermediate durational results not given in Table 10.10, the data may be plotted and a smooth curve drawn. Linear interpolation between durations is not recommended, particularly for durations less than 24 hours.

Table 10.10.--Adopted depth-duration curves for subregions identified in Table 10.8.

Subregions	Duration (Hours)				
West of Cascades	1	6	24	48	72
4	.10	.40	1.00	1.49	1.77
5	.11	.43	1.00	1.37	1.58
3	.12	.44	1.00	1.23	1.35
East of Cascades					
1	.16	.52	1.00	1.40	1.55
2	.16	.52	1.00	1.31	1.45
6	.18	.55	1.00	1.27	1.37
7	.20	.59	1.00	1.20	1.30

Table 10.11.--Comparison between storm data averages and adopted depth-duration curves for subregions 2 and 7.

Subregion	Duration (Hours) 1	6	24	48	72
2	.16	.52	1.00	1.31	1.45
storm average (12, 157, 168)	.14	.46	1.00	1.57	1.84
7	.20	.59	1.00	-	-
storm average (106, 143)	.20	.61	1.00	-	-

The subregion 4 (west of the Cascades-orographic) 15-storm average of 1.92 was also compared with Table 10.10, and showed that these storms produced a substantially greater 72/24-hour ratios than is given by the adopted subregion 4 value of 1.77. This apparent discrepancy owes primarily to the effect of storm 80, the most significant storm in the sample, which had a 72/24-hour ratio of 2.38.

Inclusion of this storm caused the average to be skewed upward, resulting in possibly excessive 72-hour PMP estimates. The rationale for accepting the 72/24-hour ratio of 1.77 for subregion 4 was based on storm data showing that storm 80 was only a controlling storm for 48 hours and beyond. This is demonstrated from the comparisons shown in Table 10.12, in which moisture maximized observed data for storm 80 (Appendix 2) were compared to PMP estimates using Tables 10.2 and 10.10.

For example, at 10-mi^2, the 24-hour depth in storm 80 is 14.45 inches (Appendix 2). The maximization factor for this storm is 1.62 (Table 7.1), so that at 24 hours and 10-mi^2, the PMP estimate is 23.44 inches or 141% of PMP. The 24-hour, 10-mi^2 estimate at the storm center is 33 inches. To obtain the 72-hour PMP estimate, this value is multiplied by 1.77 from Table 10.10 and the 72-hour, 10-mi^2 value is 58.41 inches. The maximized 72-hour, 10-mi^2 rainfall for storm 80 is 55.71 inches. The 58.41 inches divided by 55.71 inches gives 105%. Thus, storm 80 is enveloped by only 5% at 72 hours, and is indeed a controlling storm for this duration.

Table 10.12.--Percentage envelopments that PMP estimates from this study have over moisture maximized observed storm amounts for storm 80 (PMP/storm).

	Duration (Hours)				
Area (mi^2)	1	6	24	48	72
10	118	122	141	108	105
100	120	126	140	111	108
1000	100	108	131	106	106
5000	108	125	153	128	132
10000	122	136	166	143	148

A similar comparison was made for storm 106, a least-orographic storm east of the Cascades. The results shown in Table 10.13 for selected durations and areas show that the adopted PMP considerably undercuts the moisture maximized storm data. Once again, the greatest envelopments occur at 24 hours for areas less than 100-mi^2. The degree of undercutting in this storm has been accepted, primarily because of the high maximization factor (1.7 limit) for the storm. Had a lower factor been used for this storm, the level of undercutting would be reduced. PMP from this study at 1000-mi^2 and for 1 hour exceeds the observed rainfall in this storm by some 18 percent. Storm 106 also is a controlling storm for this study.

Table 10.13.--Percentage envelopments that PMP estimates from this study have over moisture maximized observed storm amounts for storm 106 (PMP/storm).

	Duration (Hours)		
Area (mi^2)	1	6	24
10	119	124	135
100	94	114	123
1000	69	97	108
5000	83	114	98
10000	100	119	95

11. LOCAL STORM PMP

11.1 Introduction

Intense localized thunderstorms during the warm season (April through October) have produced the greatest observed short-duration rainfalls over small areas in the Pacific Northwest. These storms are not usually associated with the general storms that produce widespread heavy precipitation in the cold season (November through March) in this region. This is in contrast to the eastern two-thirds of the United States, where some of the heaviest local storms are not isolated but are embedded within general and mesoscale events, even in the warm season. It is these short duration, small area storms of the Pacific Northwest that are the focus of this investigation.

Thunderstorms have been referred to in previous PMP studies as "local storms." The definition of a local storm in this study is an extreme rainfall event, not associated with widespread heavy precipitation, that produces rain for durations of 6 hours or less, and is concentrated over an area of 500-mi^2 or less. Previous definitions of local storms utilized in PMP reports for the Pacific Northwest, the southwestern United States and along the Continental Divide are quite similar in terms of the durational and areal limitations for local storms (HMR 43, 49 and 55A). These studies also maintained the need to distinguish between local storms and those embedded within a general storm rain pattern.

One of the notable differences between this study and HMR 43 is that local storm PMP was not provided for areas west of the Cascade Divide in the earlier study. The current study incorporates a much larger database of storms than did the previous study, including several major local storms that occurred west of the Cascade Divide. The most significant of these was the Aberdeen 20 NNE, Washington, storm of May 28, 1982 (Appendix 4). These new storms, with precipitation amounts in excess of 2 inches in an hour, were of sufficient magnitude to necessitate inclusion of local storm PMP estimates west of the Cascade Divide.

Less is known about the amount, durational characteristics, and areal extent of local storms than for general storms in the Pacific Northwest. The primary reason for this is that the network of precipitation observing stations in the region is still too sparse to provide useful data for many local storms. For example, station density in Oregon is about 435 square miles per station (in December 1984), while Illinois, a typical midwestern state, has a density of 349 square miles per station, which may also be inadequate. Secondly, general storms often produce precipitation over areas of thousands of square miles, while data for local convective storms in this region show that they typically produce heavy rainfalls over areas on the order of tens of square miles, sometimes less. Consequently, many extreme local storms do not show up as heavy rains even at observing stations, which may be relatively close to the storm center. Some records of intense local storms are derived from "bucket surveys," which consist of extra observations in the areas of heaviest precipitation, while accurate systematic measurements of precipitation are rarely obtainable. As a result, there is comparatively little depth-duration or depth-area data available for local storms, especially in the broad expanses of the western United States.

11.2 Record Storms

11.2.1 Introduction

The typical development of PMP for an area is based in part on major rainfalls of record. The greatest measured local storm rainfalls that have occurred in or near the Northwest are listed in Table 11.1, and their locations are shown on Figure 11.1. Table 11.1 lists the location, latitude, longitude, elevation, date, duration, total storm rainfall, and data source for each storm.

Storm elevations range from 43 to 6900 feet above sea level, with little evidence of a preferred zone within this range. The geographic distribution of these storms in Figure 11.1 appears to cut a broad path across the region from the northwest to southeast corners. The seasonal distribution of storms ranged from late May to late August. All the storms occurred during the period between 1100 and 1900 LST. Both these factors highlight the importance of solar radiation in the development of such storms, a point which is discussed in the next section.

A more extensive list of major local storms which have affected the Pacific Northwest region, was also considered (Appendix 4). Those storms represent the heaviest 1-hour rainfalls from more than 350 stations, found in the Hourly Precipitation Data (National Climatic Data Center) from July 1, 1948 through the end of 1990. Altogether 13,386 station years of data were examined. At each station, the top five hourly precipitation amounts for each month and the top ten for the entire year were isolated. To ensure that only local convective storms would be included in this database, a synoptic analysis was made of each event to eliminate any general storms. The storms were further limited by accepting only hourly precipitation totals that equalled or exceeded the 50-year hourly precipitation rainfall determined from NOAA Atlas 2. This comprehensive list, referred to as the extreme storm database, includes the storms in Table 11.1, which were not all found in Hourly Precipitation Data.

11.2.2 Meteorology of Extreme Local Storms

Extreme local storms in the Pacific Northwest are convective phenomena, primarily thunderstorms. These storms represent the controlling rainfall events for short-duration (up to 6 hours) PMP, and this section briefly considers the nature of Pacific Northwest thunderstorms.

Table 11.1.--Major Local Storms - Pacific Northwest

Location	Lat °	N '	Lon °	W '	Elev. (feet)	Date	Dur. Min.	Amount (in.)	Reference
Birch Creek, OR	45	20	118	55	3000	6/22/38	20	2.50	Riedel, et al., 1966
Skykomish 1ENE, WA	47	42	121	22	1030	5/25/45	30	1.78	Schaefer, 1989
Girds Creek, OR	44	40	120	10	4000	7/13/56	30	4.00	Riedel, et al., 1966
Simon Ranch, ID	43	15	114	45	5000	7/21/56	20	2.50	Riedel, et al., 1966
Knapp Coulee, WA	47	49	120	08	1500	8/15/56	5-10	1.50	Hendricks, 1964
Winthrop, WA	48	20	120	11	1755	7/29/58	60	3.00	Private communication
Castle Rock, WA	46	16	122	55	43	8/23/63	12	0.90	NCDC, 1963
Meridian, ID	43	37	115	25	2600	6/21/67	12	2.75	Rostvedt, 1972
John Day, OR	44	25	118	53	3200	6/9/69	180	7.00	Reid, 1975
Heppner, OR	45	20	114	33	2500	5/25/71	20	3.00	Bauman, 1980
Reynolds Creek, ID	43	15	116	45	3700	7/21/75	5	0.80	USDA, 1975
Aberdeen 20 NNE, WA	47	16	123	42	440	5/28/82	45	2.30	NCDC, 1982
BORDERING AREA									
Morgan, UT	41	03	111	38	5150	8/16/58	60	6.75	Riedel, et al., 1966
Elko, NV	40	50	115	47	5080	8/27/70	60	3.47	NCDC, 1970
Opal, WY	41	45	110	15	6900	8/16/90	120	7.00	Private communication

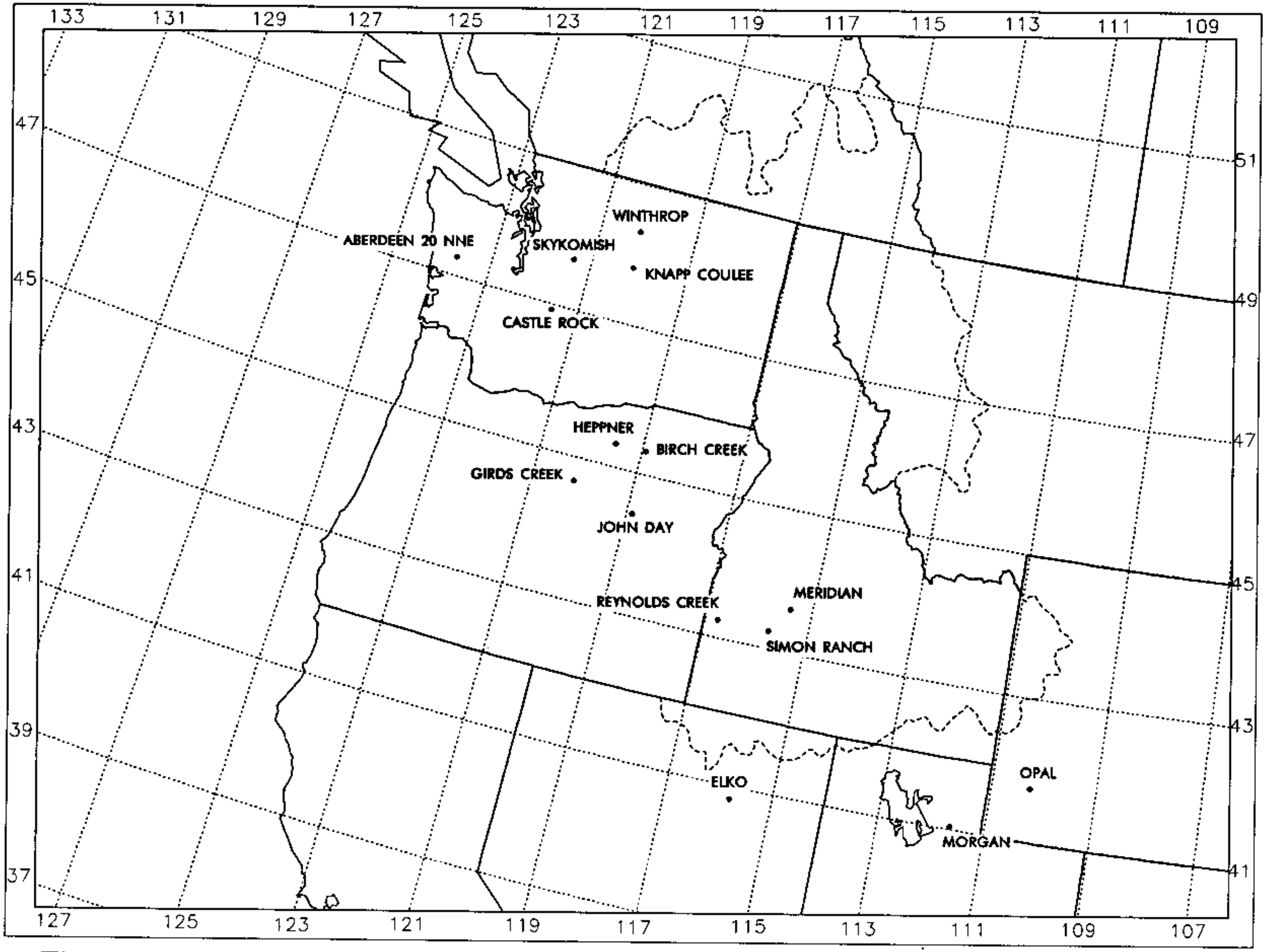

Figure 11.1.--Location of major storms of record from Table 11.1